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TRIALS AND INSTRUMENTATION DIVISION

R.A.R.D.E. MEMORANDUM 24/70

Damage effectiveness of different rod materials against various targets, at a range of velocities (C)

INV 90

Sheila E. Corbett

(44)

C 41208

PD 11396

Fort Halstead
Kent.

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October, 1970

Cat # 115627

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3

Damage effectiveness of different rod materials against various targets, at a range of velocities (C)

4

Sheila E. Corbett (F1)

Rep. 1

Continuous rod warheads
Damage assessment.

Corbett, S
AD 594464
Gt. Brit. - Continuous rod warheads

Summary

Ten materials have been placed in an 'order of merit' for damage effectiveness should they be used for the rods on Continuous Rod Warheads, by projecting rods of the various materials from explosive charges at three strike velocities against three different target materials in three thicknesses.

The dependence of damage on rod strength, density and velocity is shown to vary with target strength and thickness.

The mechanism of damage is also discussed.

Approved for issue:

Brigadier P.J.M. Pellereau, Head of 'F' Division

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1. INTRODUCTION

A continuous rod warhead is essentially a series of rods, each welded at one end to its neighbour in a zig-zag configuration, packed into two or more layers around a cylindrical explosive charge. The rods expand into a continuous hoop of large radius when the charge is fired. To do this, among other stringent requirements, the rod material must be capable of:-

(1) being explosively launched without break-up

(2) producing satisfactory hinges which will withstand the stresses incurred in opening out into the hoop

(3) remaining sufficiently ductile after launching to bend through 90° without break-up in order to achieve maximum hoop radius

(4) achieving the maximum amount of target damage

A special mild steel, STA 48A, has been developed in U.K. for continuous rod warheads and has proved satisfactory to date, but it has been suggested both here and in the U.S.A. that other materials may be equally capable of withstanding the launch and hoop expansion stages, and produce greater damage.

The object of this trial was to carry out a systematic investigation of the damaging ability of a range of possible new rod materials. It was sponsored and co-ordinated by C3 Branch, R.A.R.D.E., and was carried out in conjunction with Bristol Aerojets Ltd., who supplied the materials, conducted metallurgical tests on rods before and after launch, and ran a parallel series of experiments in which they examined the ability of rods of each material to be launched from a centrally initiated cylindrical charge, to produce satisfactory welds, and to bend through 90° (Reference 4).

2. PROGRAMME

2.1 Rod materials

The table overleaf lists the materials and their nominal mechanical properties before firing.

These metals were chosen for various reasons, some because they may be seriously considered as possible rod materials, but others chiefly to widen the range of mechanical properties covered and so help in separating the effects of the different variables involved in damage.

The first group are steels, and show Ultimate Tensile Strengths ranging from 30 to 125 tons per square inch, Elongations from 30% down to 2%, and ratios of UTS/ (% Elongation) from 1 to 60. Comparing these at a range of velocities against a variety of targets should show whether damage is dependent on the mechanical properties of the rod.

The Copper, Nickel and Monel were chosen to give a similar range of properties at a slightly higher density. Comparing Tantalum/10% Tungsten with steels of similar mechanical properties should give an indication of the effect of rod density on damage. Stainless Steel was included because the U.S. Navy is using a very similar material to manufacture continuous rod warheads, and Haynes Alloy because work in the U.S. had indicated that this material had outstanding damaging abilities.

It was hoped to relate the degree of damage to the mechanical properties, but obviously these will be changed by the explosive launch process and for this reason the properties at the instant of strike must be considered. It was therefore necessary to collect rods which had been projected, and carry out a second series of mechanical tests to determine the change in properties due to the launching process. The method for doing this is described in Reference 1, and details of the properties before and after launch are included in the present results.

Material	Density (gms/cc)	U.T.S. (tons/sq.ins)	Elong % (on 2 inch)	Crystal Structure
STA 48A (Heat treated)	7.86	29.6	30	B.C.C
3½% Ni. Steel (Heat treated)	7.85	56.6	22	B.C.C
RS 131 Steel (Heat treated)	7.85	88.0	12	B.C.C
RS 191 Maraging Steel - (aged)	8.03	125	2	F.C.C
RS 191 Maraging Steel - (overaged)	8.03	80	15	F.C.C
Copper BS 1433	8.96	25.6	16	F.C.C
Nickel A	8.90	28	44	F.C.C
K Monel	8.47	43	16	F.C.C
Tantalum/10% Tungsten	16.8	72	16	B.C.C
316 Stainless Steel (soft)	8 approx.	48	51	F.C.C
Haynes Alloy No. 25	9.22	62	39	

2.2 Velocity ranges

Three standard sizes of explosive charges were used, and these gave strike velocities of approximately 5,700 ft/sec, 4,300 ft/sec and 2,100 ft/sec. With the dense metals, these velocities were obviously somewhat reduced, but the results gave a true comparison of the effect of using different metals in a warhead of given dimensions, and by interpolation or minor extrapolation, it is possible to predict the damaging effect of the rods of denser metals when projected at the same velocity as the steel rods.

2.3 Method of projection

In previous trials to examine the effect of rod and target properties, individual rods have been projected, but for this trial the technique was modified to enable four rods to be projected from a single charge.

Doubts existed as to the wisdom of using end-initiated charges to launch the rods, because the effect of the explosive on the rod is very different from that with a centrally-initiated charge.

With a simple centrally-initiated cased cylindrical charge, both the initial pressure and the angle between the shock wave front and the wall varied considerably from the centre out to each end of the cylinder. Theoretically, the use of a suitably shaped plastic liner, should make it possible for the shock wave to arrive simultaneously at all points on the cylinder wall. However, due to the geometry of a continuous rod warhead, it is not usually possible in practice to obtain this ideal condition completely, so that the rods packed around the cylinder may be subjected to tensile and shear forces which could cause break-up in many materials.

As Reference 4 reports, where unconfined rods (no welds or end caps) are fired from centrally-initiated charge configurations which have been found satisfactory for launching STA 48A rods, considerable break-up occurs in rods made of other materials.

In an end-initiated rod projector charge, as the detonation wave proceeds down the charge, the rod is peeled off, until it finally leaves the charge at some angle to its original position, and slightly bowed in shape. The rod experiences approximately steady state conditions during the launch, and is not subjected to opposing forces such as are produced by a centrally-initiated charge. Preliminary experiments indicated that it should be possible to launch intact all the materials in this series at the range of velocities required.

The reasons for adopting end-initiated rod projectors were therefore:-

1) The damaging effects of a much wider range of materials could be compared by using end-initiation rather than central-initiation.

2) Metallurgical tests on the rods before and after launch, and measurements of initial pressure incident on the rod, suggested that changes in the structure of the metal were very similar whether the charge was end or centrally-initiated.

2.4 The targets

With a real and complex target, the degree of damage is always very dependent upon the exact position of strike and modern aircraft are so complex that shifting the strike position by as little as one inch may make a very significant difference to the degree of damage.

In this trial, where well over 1000 strikes had to be compared, the practical difficulties of obtaining this quantity of real targets, and of striking each one in identically the same place, were obviously insuperable. Even if this had been possible, the problem of assessing and comparing the degree of damage would have been formidable.

Since it is known that the rod usually fails in the tangent condition (i.e. where a large depth of metal is presented to the line of flight, such as a rod would experience after cutting half way through an aircraft fuselage) it was decided that all targets should consist of sheets of metal placed edge-on to the direction of attack with their long edge perpendicular to the axis and the line of flight of the rod. All targets were 4" deep (i.e. measured in the direction of rod flight). Three thicknesses of metal were used:-

0.036" to represent the skin of an aircraft,

0.104" to represent stringers, and

0.250" to represent main structure components.

Three target metals were used:-

Aluminium Alloy L72 and Stainless Steel EN58B to represent aircraft materials, and a high strength steel RS 141 which is used in rocket manufacture.

Although it may not be possible to build up, from these results, a picture of the damage which may be expected on a real target, the main objective here was to compare rod materials, and it seems likely that the "order of merit" would in general be equally applicable to more complex structures.

Two criteria of damage were used to compare the relative merits of different rod materials viz:-

(1) Depths of cut, which is the simplest possible measure of visible damage.

(2) Reduction in tensile strength. The percentage ratio of target strength after strike to target strength before strike has long been recognised as the ideal damage criterion because it enables an assessor to determine whether the reduction in strength of a damaged member would be sufficient to cause the aircraft to fail in flight.

3. EXPERIMENTAL PROCEDURE

3.1 The charges

A schematic diagram of the charge is shown in Figure 1, and a typical charge and layout in Figure 2. The charge projects four rods simultaneously and is described in detail in Reference 2, but for convenience, a brief description is included here.

The charge case, which was 45" long, and square in cross section, was made from ½" thick Perspex. This was filled with PE4 explosive, and initiated at one end by means of a No. 8 detonator and a 1" diameter perforated Tetryl pellet.

Each rod, which was 36" long, and 3/16" square in cross section, was butted at either end by short lengths of 3/16" square mild steel rod, and along its sides by two 3/16" thick steel guard plates. One such assembly was cemented onto each face of the Perspex box. The densities of most of the metals used are fairly close to that of mild steel, but for the Tantalum alloy rods, double thickness guard plates were used. The purpose of the guard plates and end pieces was to produce a substantially uniform loading over the whole surface of the charge, and to avoid any diffraction effects which may cause the rod to break up.

Three sizes of charge were used in order to obtain a range of velocity. Charge dimensions, and nominal rod velocities are as follows:-

Charge description	Low velocity	Medium velocity	High velocity
Rod length	36"	36"	36"
Rod cross section	3/16"	3/16"	3/16"
Guard rod lengths:- (a) detonator end (b) far end	 6" 3"	 6" 3"	 6" 3"
Guard plate dimensions	45"x½"x3/16"	45"x1"x3/16"	45"x1½"x3/16"
Metal assembly:- overall dimensions	45"x1 3/16"x3/16"	45"x2 3/16"x3/16"	45"x3 3/16"x3/16"
Perspex box- inside dimensions	1 3/16"x1 3/16"	2 3/16"x2 3/16"	3 3/16"x3 3/16"
Overall weight of filled charge	26 lbs	44 lbs	72 lbs
Weight of explosive (PE4)	4 lbs	13 lbs	27 lbs
Launch velocity for Mild Steel rod	2900 ± 100 ft/sec	4700 ± 150 ft/sec	6100 ± 200 ft/sec
Strike velocity for Mild Steel rod	2400 ± 100 ft/sec	3800 ± 150 ft/sec	4600 ± 200 ft/sec

3.2 The layout

Figure 2 shows a view of the layout with the charge placed vertically on a light wooden table in the centre of the arena. Each of the four rods attacked a separate set of targets which were mounted almost horizontally in simple wooden stands.

The location of targets, velocity gauges and butt plates was dictated largely by the geometry of the charge. Figure 3 shows a plan and side view of one lane of the layout and indicates the lines of flight of the various components. The targets were at least 15 feet away to avoid damage by the guard plates, whilst the 6 feet wide butt plates at 25 feet from the charge were intended to arrest all the debris.

The angle at which the rod was projected during launch varied with the size of the charge. It was approximately $\tan^{-1} 1/8$ downwards for the high velocity charge, $\tan^{-1} 1/10$ for the medium charge, and $\tan^{-1} 1/12$ for the low velocity charge.

The height for the charge table was calculated so that the lower end of the rod should travel 25 feet before striking the ground, and the targets were tilted backwards at the appropriate angle to the horizontal to ensure a normal strike.

In most firings, three rods were used to strike targets, whilst the fourth was recovered for metallurgical examination. Reference 3 describes the recovery method in detail.

Each target stack contained seven targets placed 6" apart. Preliminary experiments indicated that this was a sufficient spacing to prevent any interaction (i.e. each target "saw" the rod as infinitely long).

Four pairs of velocity gauges were interposed between the charge and one set of targets. Each gauge consisted of a half cylinder of Aluminium foil, $\frac{1}{2}$" diameter and 48" long, with a fine wire attached to the front of it to form a continuous circuit. A pair of gauges arranged in the form of a cross was used at each station, so that some part of the gauges was struck by the rod, whatever its deviation from the expected flight path. An Argon Lamp Chronograph was used to record the break time of each gauge, and from these results, the rod launch and strike velocities, and rates of deceleration could be calculated.

3.3 Damage measurements

Depths of cut varied from about 0.1" to over 3". Each cut was photographed in close proximity to an accurate scale, and by suitable photographic adjustments, it was possible to produce negatives in which all cuts appeared roughly the same size regardless of their actual dimension. For some of the early rounds, prints of these photographs were measured by comparison with the scale by using a graticule. Latterly the negatives were magnified to 50X using a Hilger projector, and photographic prints became unnecessary. The depth of cut was taken as the mean of the maximum and minimum depths across the thicknesses of the target.

For the tensile tests, the target was reduced to a standard 24" length with 12" on either side of the point of strike, the last 2" at each end was gripped in a friction wedge over the whole width of the material, and the specimen pulled to failure. The original strength of an undamaged target of the same dimensions was calculated from data supplied by Bristol Aerojets Ltd. The damage criterion "σ" is taken as the percentage ratio of the fail strength after strike to the original fail strength.

3.4 Metallurgical tests

Rods recovered after launching were returned to Bristol Aerojets Ltd., who measured Ultimate Tensile Strength and Elongation. Occasionally where supplies of material were short, only part of a rod was available for recovery. Sometimes the rod was not sufficiently straight or too short to permit a tensile test to be carried out. In these instances, indentation hardness measurements were taken across the cross-section of the rod, and from these an estimate of the change in U.T.S. and elongation was made.

3.5 Measurement of initial pressure on the rods

Rather special techniques were used to measure the initial pressures on the rod by the explosive.

A short length of charge with a polished rod was used, and a series of contact probes supported a short distance above the rod in an atmosphere of Propane, to prevent ionisation by the shock wave. The times of contact of the rod on the probes were recorded on an oscilloscope using simple event box circuits. The distance between adjacent probes, and their distances from the rod were carefully measured before firing. The detonation velocity was recorded separately by means of twisted wire probes embedded in the explosive at known distances apart. By subtracting the time taken for the detonation wave to travel from one probe to the next, it was possible to calculate the free surface velocity of the rod. Assuming that the free surface velocity is equal to twice the particle velocity, and using the Hugoniot relationship for Iron, it was possible to calculate the pressure incident on the rod from the detonation.

4. RESULTS

The results for depth of cut and the reduction in tensile strength of the targets after strike, are given in Tables 1 to 6 inclusive and are shown graphically in Figures 4-21. As a number of the rods cut right through the thinnest targets, only two points have been experimentally determined on some of the curves. In these cases the curve has been sketched in intuitively from the shape of those more fully determined but no claim is made for their accuracy other than at the experimental points.

Figures 22-24 show, for STA 48A, the effect of velocity on depth of cut in the three target materials.

Table 7 gives the change in metallurgical properties due to launching of the rod, and Figures 25 and 26 show the effect of rod strength on depth of cut for 0.104" thick Aluminium Alloy and Rocket Steel targets.

Measurements of initial pressure incident on the rod indicate that it is in the region of 140 Kilobars $\pm$ 15%.

During the course of these experiments, miscellaneous specimens of rod were recovered after striking the targets. Some of these are shown in Figure 27 and their significance is discussed under Section 5 of this report.

5. DISCUSSION AND CONCLUSIONS

5.1 All the rod materials used in the investigation can be launched successfully from end-initiated rod projector charges. It is not known if this would be possible from centrally-initiated charges.

5.2 There is a reasonable relationship between "σ" and "depth of cut" as a measure of damage for Aluminium Alloy targets, and to a somewhat lesser extent, with Stainless Steel targets. However, the Rocket Steel targets are comparatively brittle, and particularly with thin targets and high velocity rods, the target tends to fail by cracking, thus although the depth of cut is usually very small, the ratio "σ" becomes zero. Incipient cracking seems much more common with the brittle targets, and when a tensile load is applied, gives rise to sudden failure, so that there is a large spread in values of "σ" as can be seen by the standard deviations in Table 6.

In general, there is always more scatter in the values of "σ" than in the depths of cut. (The tables show that whereas standard deviations of the depth of cut are about 10% of the mean values with "σ" they average about 20%). Therefore less reliance could be placed on the means. Ideally a sufficient number of experiments should have been carried out to establish a reliable statistical mean for "σ" under each condition and this should have been taken as the criterion of damage, but since this was not possible, the mean depth of cut has been used as the damage criterion for comparative purposes.

5.3 It is difficult to assign an exact "order of merit" for the various metals, as this varies with conditions and in some cases possibly because of the limited number of firings. Nevertheless, the general trend is fairly obvious, and the relative damaging power of the various rod materials is given in the list below. Rods showing similar capability are grouped.

1) Tantalum/10% Tungsten

2) (Haynes Alloy
(RS 191 in both the as-received and overaged conditions

3) RS 131

4) (K Monel
(Nickel A
($3\frac{1}{2}$% Ni. Steel
(Stainless Steel

5) STA 48A

6) Copper

Tantalum/10% Tungsten may not be a practical rod material because of high cost and scarcity.

In Group 2, although Haynes Alloy is shown to be extremely good, the results of the present trial do not agree with those in Reference 5 in which Haynes Alloy was reported to have twice the penetrating power of a steel (SAE 1018) which is similar to STA 48A. Haynes Alloy is very expensive and there seems little merit in using this rather than RS 191 which is of approximately equal merit and much cheaper.

Of Group 4 materials, K Monel and Nickel A are relatively expensive and as only a limited number of tests were made with Stainless Steel, the choice in this group would appear to be $3\frac{1}{2}$% Ni. Steel.

5.4 In the following paragraphs, the effects of various parameters on damaging ability are discussed. With the limited choice of materials it was not always possible to vary each parameter of conceivable relevance independently of the others, so that there was some difficulty in analysing the data. No mathematical investigations have been made, but the graphical results strongly suggest certain trends. These trends are discussed in the following paragraphs without any claim that all of the statements can be rigorously supported mathematically. All the conclusions are drawn from the "depth of cut" data only, even though this is not always completely consistent with the "residual strength" results. Conclusions on the effect of density are based on a comparison of $3\frac{1}{2}$% Nickel Steel, K Monel, and Tantalum/10% Tungsten, since Table 7 shows that in the 'as fired' condition, the Ultimate Tensile Strengths and Elongations are in reasonably close agreement.

5.5 Against Aluminium Alloy targets, a distinction must be made between targets that are thinner and those which are thicker than the rod.

a) For targets which are thinner than the rod, the degree of damage:-

1. decreases with increasing rod velocity (Figure 22)
2. increases with increasing rod strength (Figure 25)
3. increases with increasing rod density (Figures 4 and 6, comparison of 3½% Nickel Steel, K Monel and Tantalum).

b) For targets which are of the same order of thickness as the rod, within the limits of these experiments, the degree of damage:-

1. is independent of rod velocity (Figure 22)
2. is only dependent on rod strength at low and medium velocities, but hardly so at high velocities (Figures 4, 6 and 8)
3. increases with rod density (Figures 4, 6 and 8).

c) For targets which are thicker than the rod, the evidence is not so clear cut but trends, particularly in association with previous findings on thicker targets, suggest that the degree of damage:-

1. increases slightly with rod velocity (Figure 22)
2. depends only to a moderate degree on rod strength at low velocities, but hardly at all at medium and high velocities (Figures 4, 6 and 8)
3. increases with rod density (comparing 3½% Nickel Steel and Tantalum on Figures 4, 6 and 8).

5.6 For Stainless Steel targets, the pattern is much the same at the lower velocities although the damage is relatively less (Figures 10 and 12). However at high velocities, the rod velocity appears to be the dominant parameter and within the limits of these experiments damage is virtually independent of target thickness, rod density and strength, Figure 14 shows that the effects of change of rod materials and target thickness are small but a comparison between Figures 12 and 14, nevertheless shows a significant increase in damage with increase of velocity, except for the thin targets.

5.7 Against Rocket Steel targets, where the damage is small compared with Aluminium Alloy, so that it is difficult to resolve small differences, within the limits of these trials, the trend appears to be:-

a) For targets thinner than the rod:-

1. damage is independent of rod velocity (Figures 16, 18 and 20 with the possible exception of Tantalum)
2. damage is independent of rod strength (Figure 20 - damage of RS 191 and STA 48A very similar compared with approximate 2:1 against Aluminium Alloy targets).
3. at low velocities, density is important, although this trend disappears as rod velocity increases (Figures 16, 18 and 20).

b) For targets thicker than the rod, the damage is very slight - nothing more than an 0.15" cut was achieved, but a vast spread in residual strengths was measured, due, no doubt, to the brittle nature of the target material.

5.8 Figures 21, 22 and 23 show the effect of velocity for one rod material against the three types of target. On the assumption that thin targets of Aluminium Alloy or Stainless Steel placed edge-on to the direction of attack are representative of modern aircraft, then a low velocity rod would do the most damage.

5.9 Figures 25 and 26 show the effect of rod strength on damage, and indicate that it is nearly always an advantage to use high strength rod materials, whatever the target.

5.10 From the evidence accumulated during this trial, the following mechanisms of damage are postulated.

Figure 27 (a) shows a rod which had cut through a 4" deep 0.036" thick Aluminium Alloy target and sustained virtually no damage. The contour shows how a length of approximately 3" either side of the point of impact had been formed into an arc, and that there was a little local thinning of the rod at the point of contact with the target, whilst the remainder of the rod remained comparatively straight and unaffected by the impact. Some Aluminium had been deposited on the rod for about $\frac{1}{4}$" either side of the strike point.

When a rod strikes an edge-on target, the portion in contact with the target is immediately decelerated to the "cutting" velocity. Provided the yield strength of the target is low enough, the rod is pulled into the target by the portion of rod on either side of the impacting region at this constant cutting velocity, and energy is gradually absorbed to maintain this speed against the work done on the target, and in effect a bending wave moves out along the rod as successive elements are decelerated. During this time, all the rod between the two out-moving bending waves is in tension.

The process can be halted in one of three ways:-

1. the target is defeated, as in Figure 27 (a).
2. the bending waves reach the end of the rod, and no further energy is available, so the rod is brought to rest.
3. local tensile failure due to excess thinning occurs at the point of contact. Obviously with a faster rod, the tensile forces will be greater and local failure will occur earlier - hence the better performance of low velocity rods. The advantage of high strength rods is also obvious - they can sustain higher tensile forces before local failure occurs.

Against thicker targets, the rod tends to fail on both edges of the target, and Figure 27 (b) shows a small piece of rod which was trapped in a 0.104" thick target. After rod failure, the portion associated with the target is brought to rest, deepening the cut by virtue of its kinetic energy, and is therefore dependent on rod density and residual velocity.

As target thickness increases, the work done against it by the rod will increase, hence, the rate of feed-in of energy will increase, and the tensile force on the rod will be greater. Therefore the thicker the target, the sooner the rod will fail. This means that a greater proportion of the total work will be carried out by the residual fragment, and therefore the total damage will be less dependent on rod strength and more dependent on rod density.

Figure 27 (c) shows a recovered fragment of rod which had been associated with a 2" thick Aluminium Alloy target. It can be seen that:-

1. both ends failed in tension, and
2. that the fragment is curved to the contour of the cut made in the target indicating that it was being pulled through the target by the adjoining sections of the rod.
3. a careful weighing indicated that the loss in mass in this section of the rod was very small, and therefore erosion of the rod during the penetrating process was small.

When the target material has a yield stress in tension which is greater than the ultimate shear strength of the rod, the rod very quickly fails in shear. This occurred with most rods against Rocket Steel targets - hence the small depth of cut, and the fact that strength of rod had very little effect on penetration. Figure 27 (d) shows a rod tension failure whilst Figure 27 (e) shows a shear failure.

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7. ACKNOWLEDGEMENTS

This work was undertaken on behalf of C3 Branch, R.A.R.D.E., and their advice and guidance at all stages is much appreciated.

It is also a pleasure to acknowledge the contribution of Messrs: R. Dyer and B. Sutton of D2 Branch, for their advice on metallurgical problems and their investigations into tensile tests; of Messrs: M. Turner, J. Bateman and G. Lees of Bristol Aerojets Ltd; for their metallurgical tests and advice, and of Mr. B.J. Paterson of this Branch for his contribution to the instantaneous pressure measuring experiments.

TABLE 1 Rod Projector Results against Aluminium Alloy Targets

Rod Condition		Target Thickness - ins.	All Targets 4" deep back to front.	
Rod Material	Rod Strike Velocity (ft/sec)	0.036	0.104	0.250
		(1) Depth of Cut - Inches		
STA 48A	4600	0.864 ± 0.102 (6)	0.737 ± 0.50 (6)	0.665 ± 0.055 (9)
	3800	1.858 ± 0.350 (6)	0.895 ± 0.99 (7)	0.646 ± 0.046 (6)
	2400	4" + (cut through)(4)	0.876 ± 0.100 (7)	0.479 ± 0.044 (8)
3½% Ni Steel	4600	1.196 ± 0.184 (5)	0.759 ± 0.077 (5)	0.699 ± 0.084 (6)
	3800	2.756 ± 0.528 (6)	1.053 ± 0.070 (6)	0.665 ± 0.094 (6)
	2400	4" + (cut through)(7)	1.068 ± 0.015 (5)	0.555 ± 0.036 (6)
RS 131	4600	1.643 ± 0.818 (6)	0.807 ± 0.060 (6)	0.764 ± 0.080 (6)
	3600	2.762 ± 0.216 (3)	1.382 ± 0.214 (6)	0.716 ± 0.087 (6)
	2400	4" + (cut through)(6)	1.409 ± 0.130 (7)	0.628 ± 0.084 (8)
Cu 1433	4500	0.672 ± 0.062 (3)	0.639 ± 0.102 (3)	0.677 ± 0.081 (4)
	3700	0.798 ± 0.051 (2)	0.538 ± 0.003 (3)	0.530 ± 0.014 (4)
	2400	1.079 ± 0.015 (2)	0.410 ± 0.011 (2)	0.374 ± 0.033 (3)
K Monel	4700	1.112 ± 0.216 (9)	0.791 ± 0.067 (7)	0.909 ± 0.193 (4)
	3200	2.357 ± 0.303 (8)	1.183 ± 0.353 (5)	0.617 ± 0.020 (4)
	2000	4" + (cut through)(10)	1.157 ± 0.157 (5)	0.550 ± 0.052 (4)
St Steel	4400	0.868 ± 0.063 (2)	0.815 ± 0.035 (2)	0.842 ± 0.080 (5)
	4200	1.917 ± 0.033 (2)	0.860 ± 0.102 (4)	0.675 ± 0.084 (2)
	2300	4" + (cut through)(4)	1.215 ± 0.050 (4)	0.559 ± 0.018 (3)
Haynes Alloy	4300	3.272 ± 0.561 (5)	1.297 ± 0.470 (4)	0.866 ± 0.166 (5)
	4000	4" + (cut through)(4)	1.804 ± 0.514 (7)	0.840 ± 0.129 (5)
	2200	4" + (cut through)(3)	1.341 ± 0.038 (6)	0.625 ± 0.043 (9)
RS 191	4600	2.777 ± 0.116 (3)	0.850 ± 0.074 (4)	0.710 ± 0.037 (5)
	3800	4" + (cut through)(4)	1.412 ± 0.240 (6)	0.777 ± 0.189 (5)
	2400	4" + (cut through)(4)	1.743 ± 0.078 (6)	0.733 ± 0.078 (9)
RS 191 Overaged	4400	2.980 ± 1.305 (5)	1.065 ± 0.172 (4)	0.748 ± 0.030 (4)
	4200	4" + (cut through)(3)	1.926 ± 0.507 (6)	0.820 ± 0.141 (2)
	2300	3" + (cut through)(4)	2.231 ± 0.303 (4)	0.700 ± 0.026 (3)
Tantalum	4100	4" + (cut through)(3)	2.257 ± 0.300 (2)	1.052 ± 0.009 (2)
	2300	4" + (cut through)(3)	2.549 ± 0.691 (2)	1.214 ± 0.034 (2)
	1700	4" + (cut through)(3)	2.390 ± 0.023 (3)	0.719 ± 0.006 (2)
Nickel A	4400	0.959 ± 0.093 (6)	0.854 ± 0.053 (6)	0.778 ± 0.080 (5)
	3600	2.015 ± 0.644 (6)	0.880 ± 0.044 (6)	0.607 ± 0.044 (6)
	2100	4" + (cut through)(7)	1.120 ± 0.169 (6)	0.501 ± 0.023 (5)

TABLE 2 Rod Projector Results against Aluminium Alloy Targets

Rod Condition		Target Thickness - ins. All Targets 4" deep back to front		
Rod Material	Rod Strike Velocity (ft/sec)	0.036	0.104	0.250
		(2) (Residual Strength/Original Strength)%		
STA 48A	4600	21.4 ± 16.0 (6)	34.7 ± 4.5 (7)	43.2 ± 5.5 (9)
	3800	14.0 ± 4.2 (4)	33.4 ± 2.3 (4)	40.5 ± 2.6 (7)
	2400	0 (2)	26.6 ± 7.9 (8)	44.9 ± 3.0 (8)
3½% Ni Steel	4600	22.5 ± 4.8 (3)	35.6 ± 2.6 (6)	38.9 ± 1.3 (6)
	3800	0 (3)	26.6 ± 5.5 (4)	42.5 ± 4.1 (6)
	2400	0 (6)	30.4 ± 8.4 (8)	45.7 ± 4.7 (6)
RS 131	4600	24.7 (1)	31.2 ± 3.3 (5)	38.4 ± 3.8 (6)
	3600	0 (1)	20.3 ± 4.1 (6)	41.2 ± 4.9 (6)
	2400	0 (5)	17.4 ± 2.4 (7)	41.6 ± 3.3 (8)
Cu 1433	4500	30.3 ± 3.0 (2)	40.6 ± 8.1 (2)	44.9 ± 3.1 (4)
	3700	21.7 ± 8.0 (2)	47.6 ± 4.1 (3)	45.5 ± 1.4 (4)
	2400	27.6 ± 2.6 (3)	48.5 ± 4.6 (2)	46.5 ± 1.5 (3)
K Monel	4700	22.3 ± 10.0 (3)	47.7 ± 11.4 (4)	45.4 ± 7.0 (4)
	3200	0 (7)	35.4 ± 13.8 (5)	49.5 ± 0.7 (4)
	2000	0 (10)	27.1 ± 2.9 (5)	53.9 ± 4.0 (4)
St. Steel	4400	0 (2)	39.5 (1)	40.5 ± 3.8 (4)
	4200	0 (3)	37.7 ± 4.6 (4)	47.4 ± 4.2 (2)
	2300	0 (4)	30.9 ± 1.7 (4)	48.2 ± 0.8 (3)
Haynes Alloy	4300	0 (1)	29.6 ± 2.8 (3)	39.7 ± 3.8 (7)
	4000	0 (4)	15.8 ± 3.1 (4)	36.5 ± 2.0 (4)
	2200	0 (3)	20.0 ± 2.5 (6)	41.7 ± 4.4 (9)
RS 191	4600	0 (4)	25.0 ± 13.7 (6)	36.0 ± 2.4 (5)
	3800	0 (4)	18.6 ± 4.3 (6)	38.5 ± 3.8 (5)
	2400	0 (4)	13.1 ± 2.8 (6)	36.7 ± 1.2 (5)
RS 191 Overaged	4400	0 (4)	35.4 ± 7.2 (5)	42.5 ± 3.1 (4)
	4200	0 (3)	19.5 ± 11.8 (6)	39.9 ± 3.4 (2)
	2300	0 (4)	20.7 ± 7.2 (4)	43.1 ± 3.6 (3)
Tantalum	4100	0 (1)	17.3 ± 0.7 (2)	35.8 ± 10.1 (4)
	2300	0 (1)	8.2 (1)	34.0 ± 8.1 (4)
	1700	0 (1)	7.2 ± 1.0 (2)	45.4 ± 1.9 (2)
Nickel A	4400	33.0 ± 0.8 (2)	38.7 ± 1.8 (5)	41.5 ± 4.3 (6)
	3600	23.8 ± 8.0 (4)	37.9 ± 7.1 (7)	48.3 ± 3.8 (6)
	2100	0 (7)	30.5 ± 2.6 (5)	50.3 ± 3.1 (5)

TABLE 3

Rod Projector Results against Stainless Steel Targets

Rod Condition		Target Thickness - ins.		All Targets 4" deep back to front		
Rod Material	Rod Strike Velocity (ft/sec)	0.036	0.048	0.104	0.188	0.250
		(1) Depth of cut				
STA 48A	4600	0.442 ± 0.018 (4)	0.339 ± 0.021 (4)	0.369 ± 0.017 (7)	0.370 ± 0.034 (3)	0.370 ± 0.017 (3)
	3800	0.452 ± 0.015 (6)	-	0.319 ± 0.024 (6)	0.308 ± 0.017 (5)	-
	2400	0.699 ± 0.071 (8)	-	0.288 ± 0.020 (8)	0.223 ± 0.020 (7)	-
$3\frac{1}{2}\%$ Ni Steel	4600	-	0.404 ± 0.046 (3)	0.373 ± 0.043 (4)	0.395 ± 0.022 (2)	-
	3800	0.515 ± 0.018 (4)	0.458 ± 0.014 (5)	0.362 ± 0.036 (8)	0.321 ± 0.023 (3)	0.329 ± 0.014 (4)
	2400	1.112 ± 0.184 (4)	-	0.393 ± 0.028 (5)	0.249 ± 0.020 (8)	-
RS 131	4600	-	-	-	-	-
	3600	0.616 ± 0.015 (2)	-	0.396n ± 0.001 (2)	0.327 ± 0.020 (5)	-
	2400	1.940 ± 0.019 (3)	-	0.555 ± 0.128 (4)	0.303 ± 0.022 (5)	-
K Monel	4700	-	0.406 ± 0.032 (3)	0.363 ± 0.012 (3)	-	0.384 ± 0.026 (3)
	3200	-	0.451 ± 0.005 (3)	0.335 ± 0.004 (3)	±	0.307 ± 0.031 (5)
	2000	-	0.857 ± 0.177 (3)	0.387 ± 0.046 (4)	-	0.241 ± 0.010 (3)
RS 191	4600	0.502 ± 0.010 (3)	-	0.390 ± 0.051 (5)	0.373 ± 0.0 (2)	-
	3800	-	0.549 ± 0.035 (3)	0.412 ± 0.069 (5)	-	0.299 ± 0.009 (3)
	2400	-	-	-	-	-
Tantalum	4100	-	0.503 (1)	1.157 (1)	-	0.422 ± 0.009 (2)
	2300	-	0.668 (1)	0.401 (1)	-	0.305 (1)
	1700	-	3.461 ± 0.249 (2)	0.657 (1)	0.288 ± 0.002 (2)	-

TABLE 4

Rod Projector Results against Stainless Steel Targets

Rod Condition		Target Thickness - ins.	Targets 4" deep back to front			
Rod Material	Rod Strike Velocity (ft/sec)	0.036	0.048	0.104	0.188	0.250
		(2) (Residual Strength/Original Strength)%				
STA 48A	4600	56.3 ± 3.6 (3)	52.9 ± 4.2 (4)	63.5 ± 5.5 (4)	57.1 ± 0.4 (2)	61.9 ± 0.1 (2)
	3800	61.6 ± 8.6 (4)	-	66.2 ± 2.9 (5)	61.9 ± 2.2 (4)	-
	2400	48.7 ± 2.3 (5)	-	64.3 ± 3.9 (7)	64.9 ± 3.3 (5)	-
$3\frac{1}{2}$% Ni Steel	4600	-	55.1 ± 7.0 (3)	62.1 ± 4.3 (3)	70.5 ± 4.7 (2)	-
	3800	49.7 ± 1.2 (2)	-	61.2 ± 7.2 (7)	64.6 ± 2.8 (3)	64.1 ± 1.9 (4)
	2400	40.3 ± 3.3 (4)	-	61.2 ± 5.0 (4)	67.5 ± 7.9 (8)	-
RS 131	4600	-	-	-	-	-
	3600	46.8 ± 0.7 (2)	-	61.1 ± 5.9 (3)	64.1 ± 3.2 (5)	-
	2400	23.0 ± 3.0 (4)	-	49.5 ± 1.1 (3)	60.5 ± 2.2 (3)	-
K Monel	4700	-	52.5 ± 2.2 (2)	55.7 ± 0.8 (2)	-	65.9 ± 9.3 (3)
	3200	-	48.9 ± 2.72 (2)	59.0 ± 1.5 (4)	-	62.0 ± 3.1 (4)
	2000	-	-	55.1 ± 0.7 (2)	-	58.8 - (1)
RS 191	4600	68.6 ± 0.2 (3)	-	58.3 ± 2.9 (5)	75.9 ± 0.1 (2)	-
	3800	-	57.6 ± 1.3 (3)	55.6 ± 3.5 (5)	-	62.2 ± 1.3 (3)
	2400	-	-	-	-	-
Tantalum	4100	-	-	-	-	58.5 ± (1)
	2300	-	-	60.4 (1)	-	62.8 (1)
	1700	-	14.4 (1)	54.2 (1)	-	68.5 ± 2.5 (2)

TABLE 5 Rod Projector Results against Rocket Steel Targets

Rod Condition		Target Thickness - ins.	All Targets 4" deep back to front	
Rod Material	Rod Strike Velocity (ft/sec)	0.036	0.104	0.250
(1) Depth of Cut (inch)				
STA 48A	4600	0.266 ± 0.040 (5)	0.230 ± 0.012 (5)	0.287 ± 0.026 (4)
	3800	0.274 ± 0.020 (2)	0.219 ± 0.0 (2)	0.258 (1)
	2400	0.218 ± 0.031 (2)	0.107 ± 0.001 (2)	0.153 ± 0.002 (3)
$3\frac{1}{2}\%$ Ni	4600	0.295 ± 0.026 (4)	0.284 ± 0.011 (3)	0.289 ± 0.090 (3)
	3800	0.316 ± 0.072 (4)	0.207 ± 0.020 (6)	0.217 ± 0.029 (4)
	2400	0.353 ± 0.008 (2)	0.156 ± 0.006 (2)	-
RS 131	4600	0.257 ± 0.017 (2)	-	-
	3600	- 0.325 (1)	0.227 ± 0.005 (4)	-
	2400	-	-	-
Cu 1433	4500	0.293 ± 0.030 (2)	0.230 ± 0.009 (2)	-
	3700	0.209 ± 0.010 (2)	0.186 (1)	-
	2400	-	-	-
K Monel	4700	0.282 ± 0.012 (3)	0.255 ± 0.009 (5)	0.285 ± 0.020 (4)
	3200	0.282 ± 0.003 (2)	0.208 ± 0.018 (3)	0.229 ± 0.006 (3)
	2000	0.332 ± 0.029 (5)	0.142 ± 0.106 (5)	0.118 ± 0.021 (3)
RS 191	4600	0.358 ± 0.005 (2)	0.295 ± 0.053 (3)	0.261 ± 0.013 (2)
	3800	0.390 ± 0.073 (5)	0.214 ± 0.012 (3)	-
	2400	-	-	-
Tantalum	4100	0.355 ± 0.028 (2)	0.299 ± 0.028 (3)	0.264 (1)
	2300	0.362 ± 0.047 (3)	0.206 ± 0.024 (3)	0.198 ± 0.191 (2)
5	1700	1.350 ± 0.039 (2)	0.184 ± 0.020 (2)	0.130 ± 0.0 (2)

Rod Projector Results against Rocket Steel Targets

TABLE 6

Rod Condition		Target Thickness - ins.	All Targets 4" deep back to front	
Rod Material	Rod Strike Velocity (ft/sec)	0.036	0.104	0.250
		(2) Residual Strength/Original Strength%		
STA 48A	4600	70.7 ± 15.7 (2)	-	42.2 (1)
	3800	64.3 ± 7.6 (2)	-	48.3 (1)
	2400	75.3 ± 5.4 (2)	77.3 ± 8.5 (2)	56.3 ± 1.7 (3)
3½% Ni Steel	4600	63.5 ± 1.0 (2)	74.1 ± 12.2 (2)	46.9 ± 3.1 (3)
	3800	-	64.9 ± 6.8 (2)	72.3 ± 11.6(4)
	2400	52.3 ± 4.6 (2)	82.4 ± 5.1 (2)	6
RS 131	4600	-	-	-
	3600	53.7 (1)	61.8 ± 13.5 (4)	-
	2400	-	-	-
Cu 1433	4500	47.9 ± 6.9 (2)	75.1 ± 0.5 (2)	-
	3700	84.2 ± 5.0 (2)	74.3 (1)	-
	2400	-	-	-
K Monel	4700	13.1 ± 3.9 (3)	60.2 ± 9.5 (5)	64.5 ± 13.3(4)
	3200	76.8 ± 9.6 (4)	-	54.1 ± 2.0 (3)
	2000	74.8 ± (1)	72.3 ± 6.1 (4)	64.6 ± 9.6 (2)
RS 191	4600	-	55.6 ± 8.4 (3)	57.1 ± 2.8 (2)
	3800	63.3 ± 5.6 (3)	61.7 ± 10.0 (3)	-
	2400	-	-	-
Tantalum	4100	19.2 ± 4.0 (2)	55.2 ± 4.141(3)	65.3 (1)
	2300	80.5 ± 0.7 (2)	66.7 ± 21.0 (3)	79.2 (1)
	1700	-	67.7 ± 10.1 (2)	74.6 ± 3.2 (2)

TABLE 7

PROPERTIES OF MATERIALS LAUNCHED AT DIFFERENT VELOCITIES

Material	Condition	Launch Velocity (ft/sec)	U.T.S. (Tons/sq.ins)	Elongation %
STA 48A (Mild Steel)	Hardened and Tempered	Before firing 2,900 4,700 6,100	31.9 42.1 57.9 63.4	31 25 15.2 12.9
3½% NI Steel	Hardened and Tempered	Before firing 2,900 4,800 6,100	61.9 67.9 85.7 87.0	19.5 20.0 12.7 10.5
RS 131 1% Cr.Mo.Steel	Hardened and Tempered	Before firing	83.0 88.0 100.3 102	15.0 12.6 13.0 12.2
RS 191 Maraging Steel	As rolled	Before firing 4,500 6,100	73 137.5 139.5	12.0 8.0 7.2
RS 191 Maraging Steel	Overaged	Before firing	80	15
Copper BS.1433	Tough Pitch	Before firing After firing	25.6 Virtually no change	16
Nickel A	As rolled	Before firing 2,830 4,220 6,100	45 56 53.2 55*	17.5 10.0 11.1 10.5*
K Monel	As rolled	Before firing 2,800 4,500 6,000	43.0 69.7 75 80*	16.0 8.3 6.0 5*
Tantalum Alloy (10% Tungsten)	As drawn	Before firing 2,500	67.2 71.4 75* 79*	20.5 17.4 14* 10*
316 Stainless Steel	As rolled	Before firing After firing	41.0 50+*	36.0 16*
Haynes Alloy No 25	As rolled	Before firing 2,700 4,500 6,000	62 117 120* 120	39 4.0 5.0 5.3

*Estimated because no tensile tests available.

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FIG.1

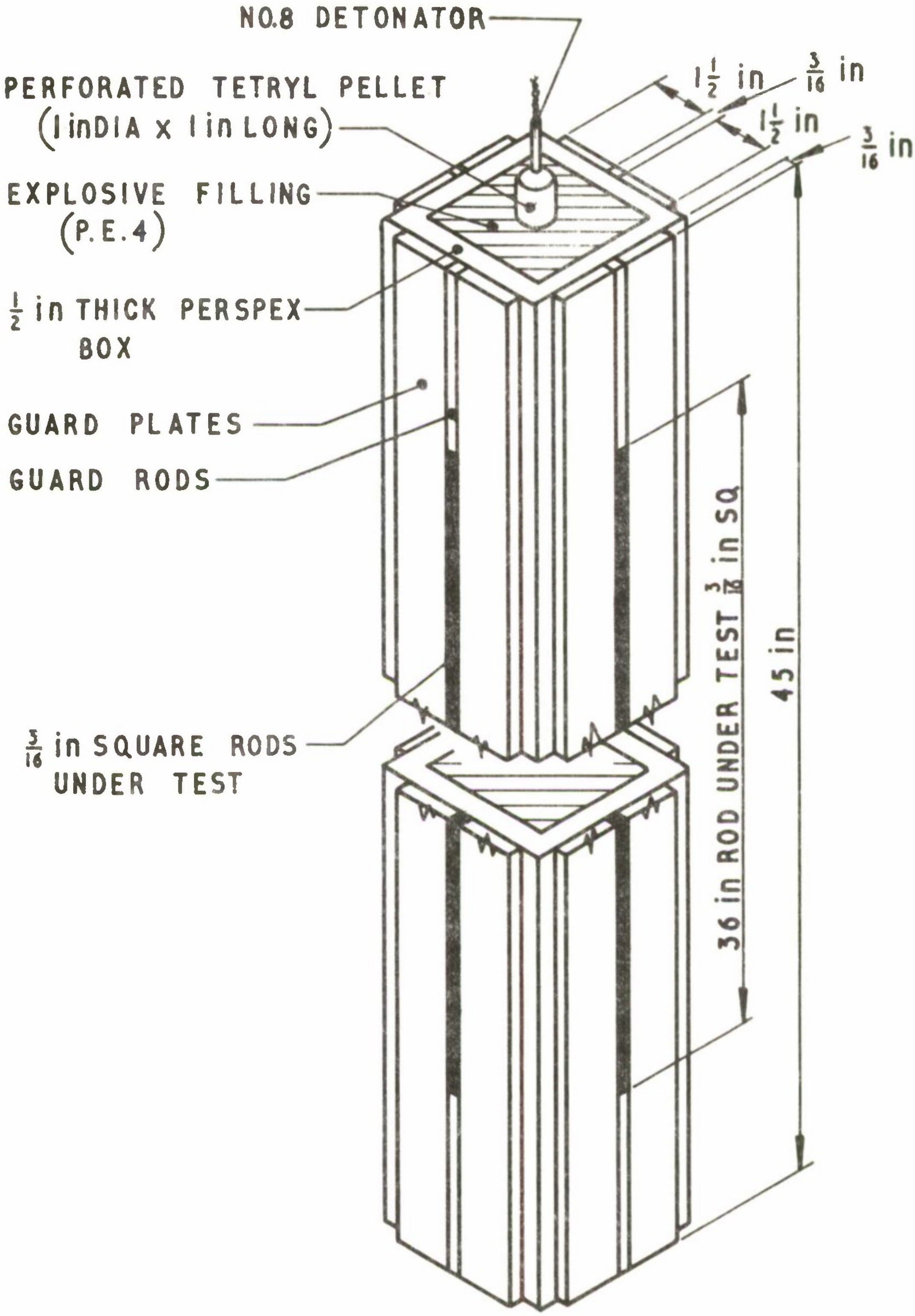

FIG.1 SCHEMATIC DIAGRAM OF CHARGE

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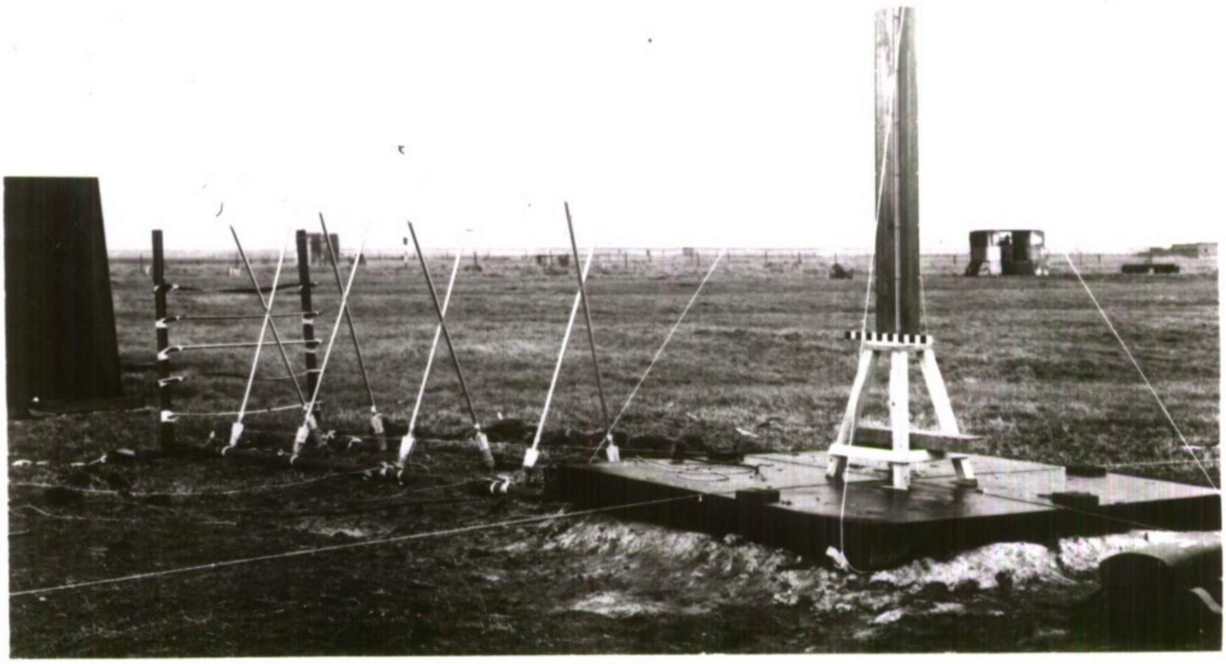

FIG. 2 GENERAL VIEW OF LAYOUT

FIG.3

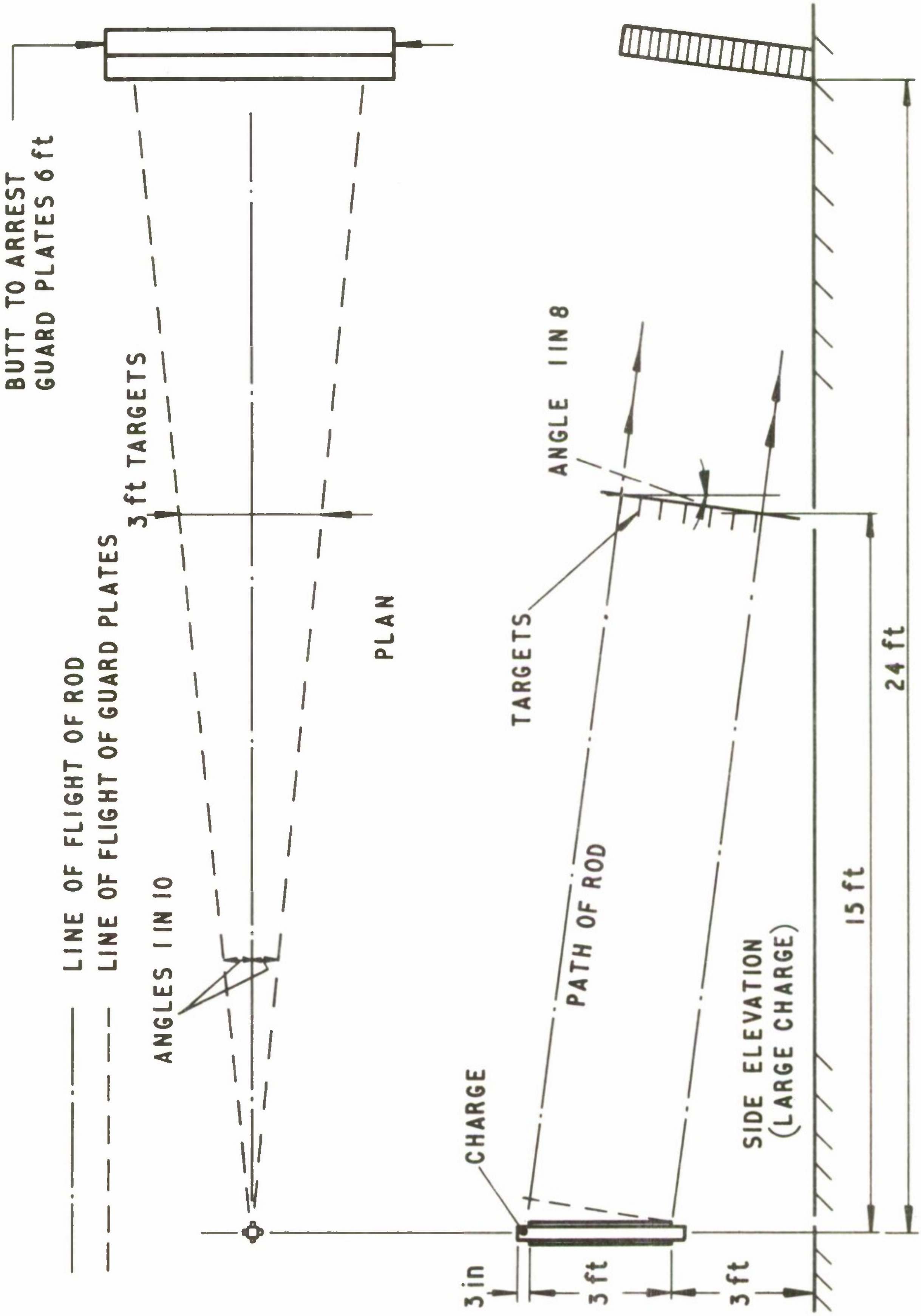

FIG.3 FLIGHT PATHS OF VARIOUS CHARGE COMPONENTS

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FIG.4

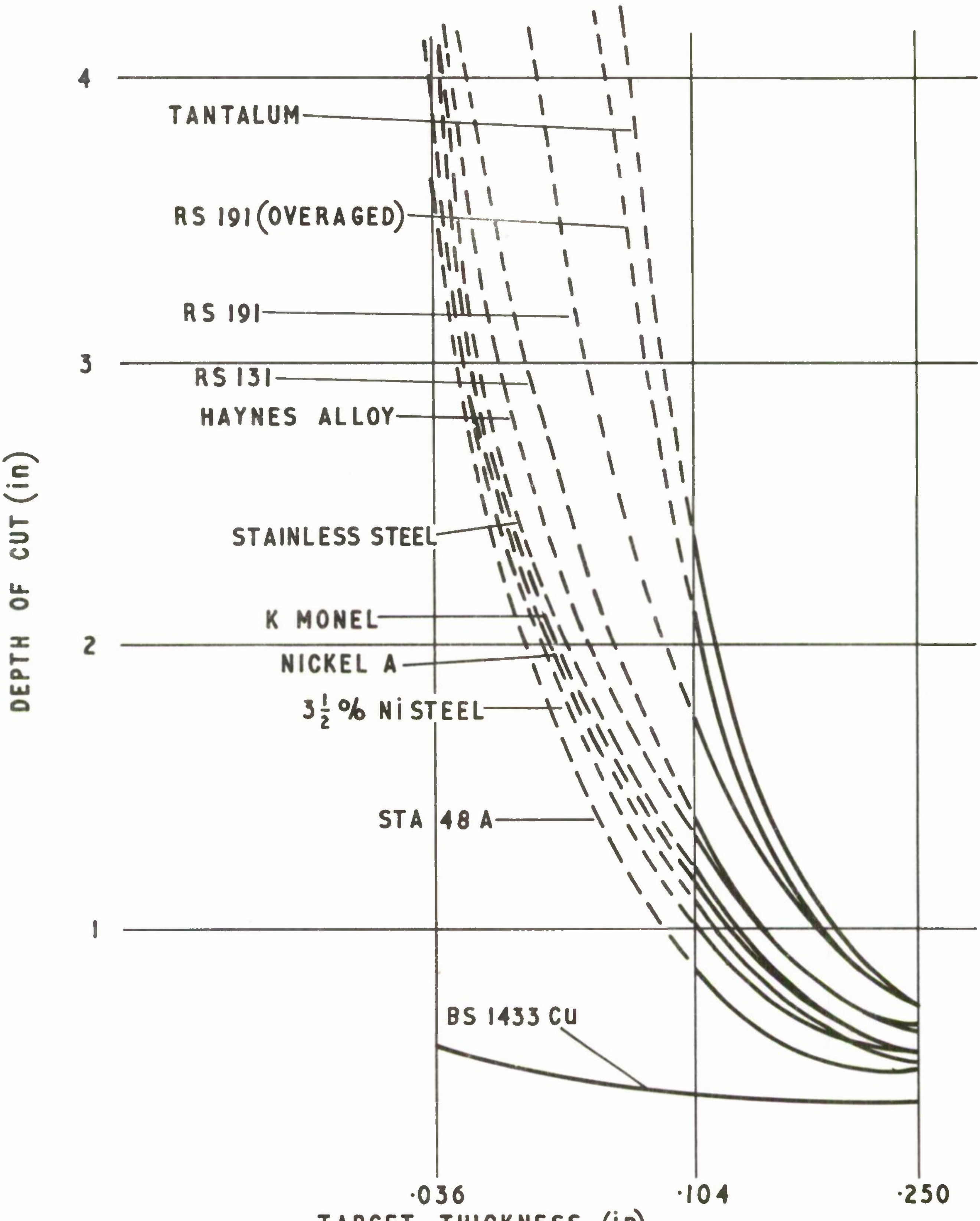

FIG. 4 DEPTHS OF CUT IN ALUMINIUM ALLOY TARGETS FROM LOW VELOCITY RODS

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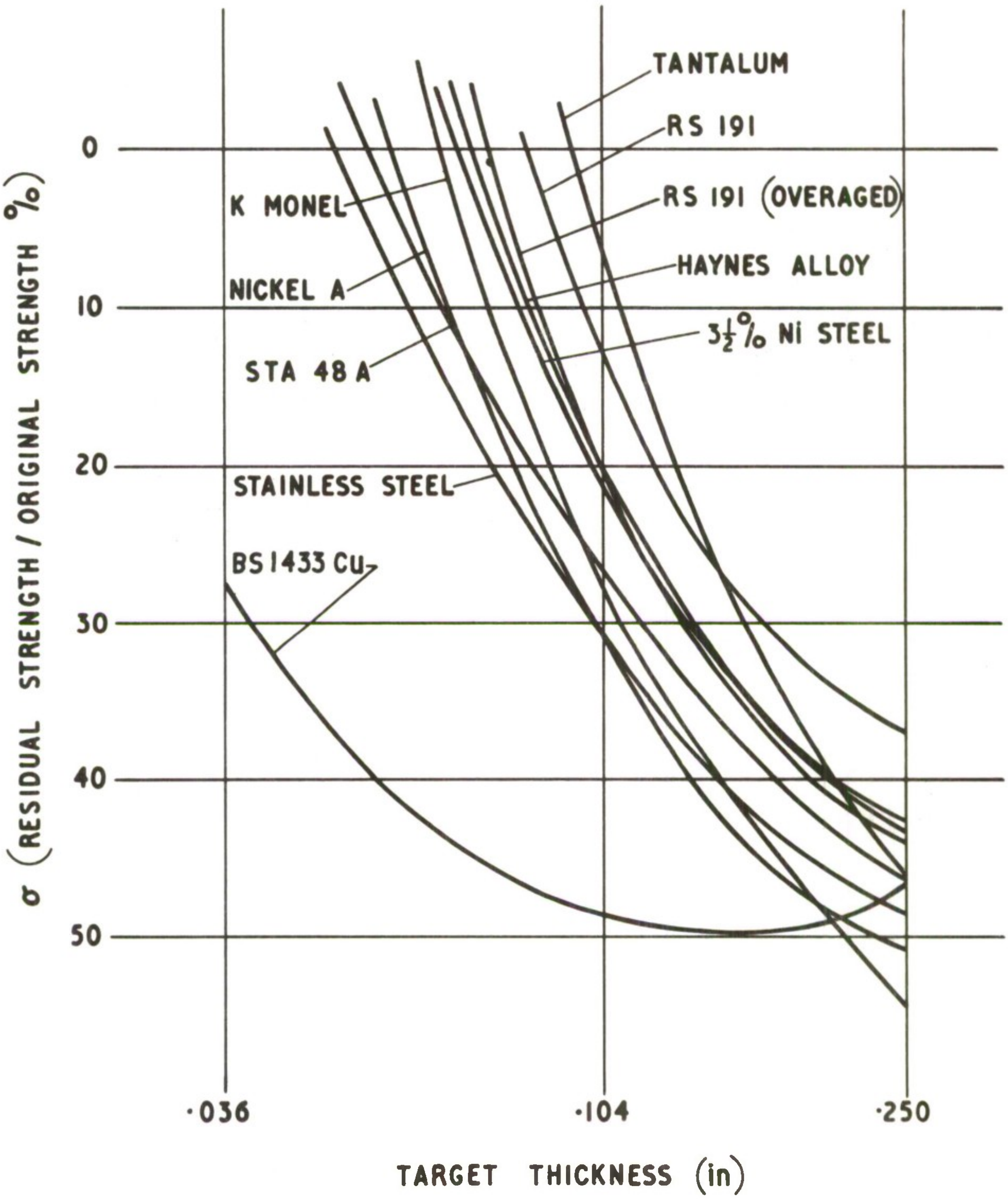

FIG. 5 RESIDUAL STRENGTHS OF ALUMINIUM ALLOY TARGETS FROM LOW VELOCITY RODS

FIG. 6

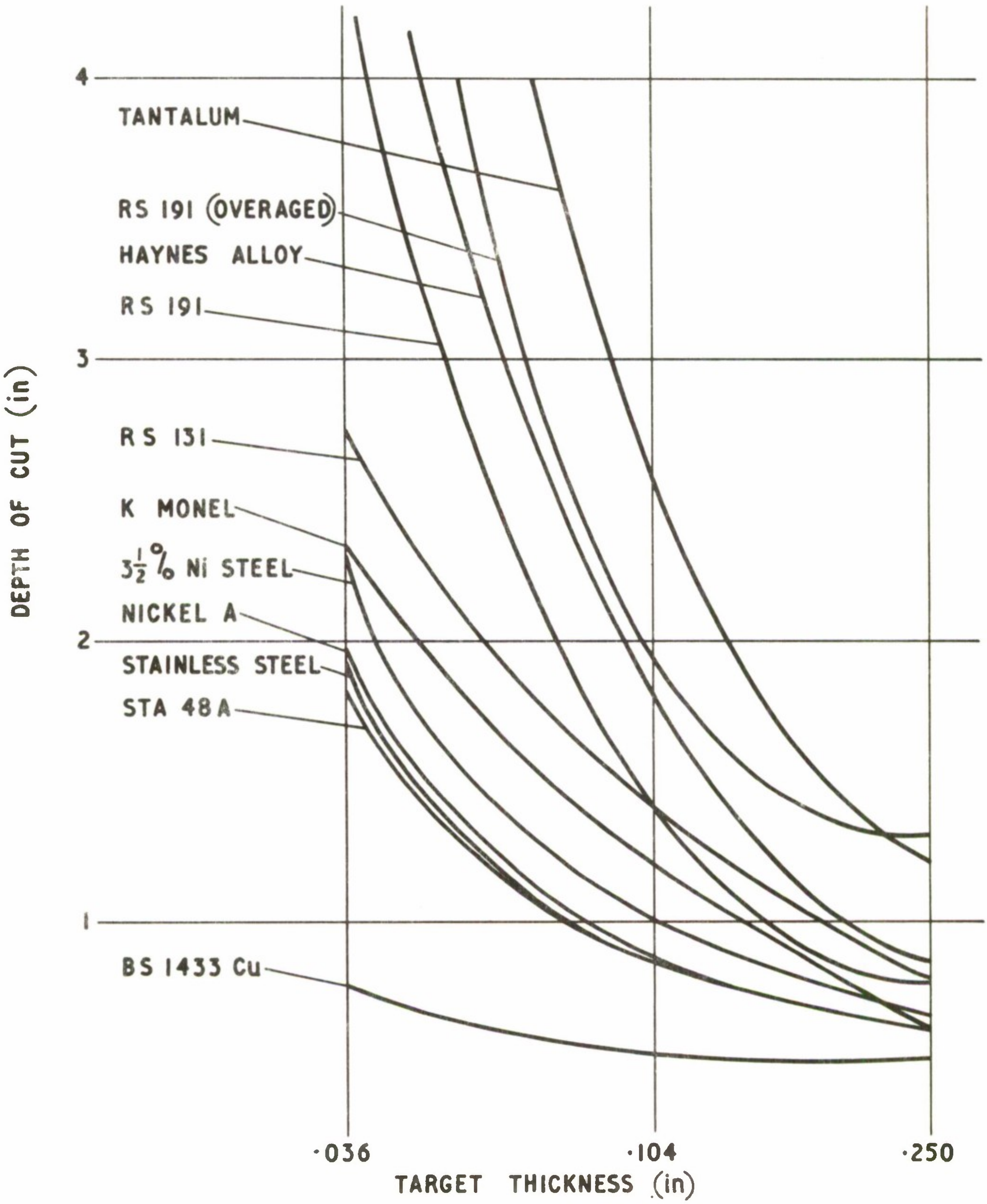

FIG. 6 DEPTHS OF CUT IN ALUMINIUM ALLOY TARGETS FROM MEDIUM VELOCITY RODS

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FIG. 7

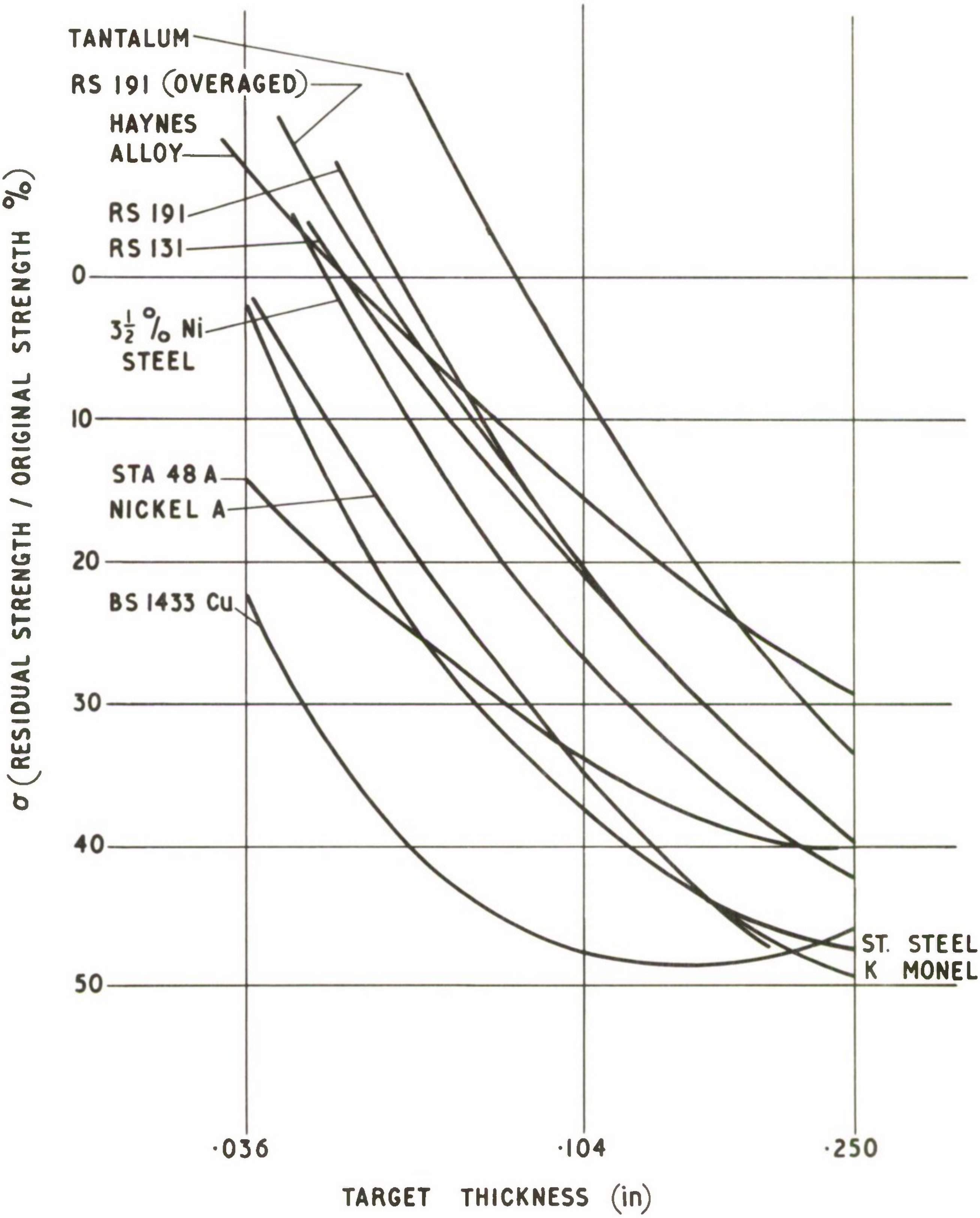

FIG. 7 RESIDUAL STRENGTHS OF ALUMINIUM ALLOY TARGETS FROM MEDIUM VELOCITY RODS

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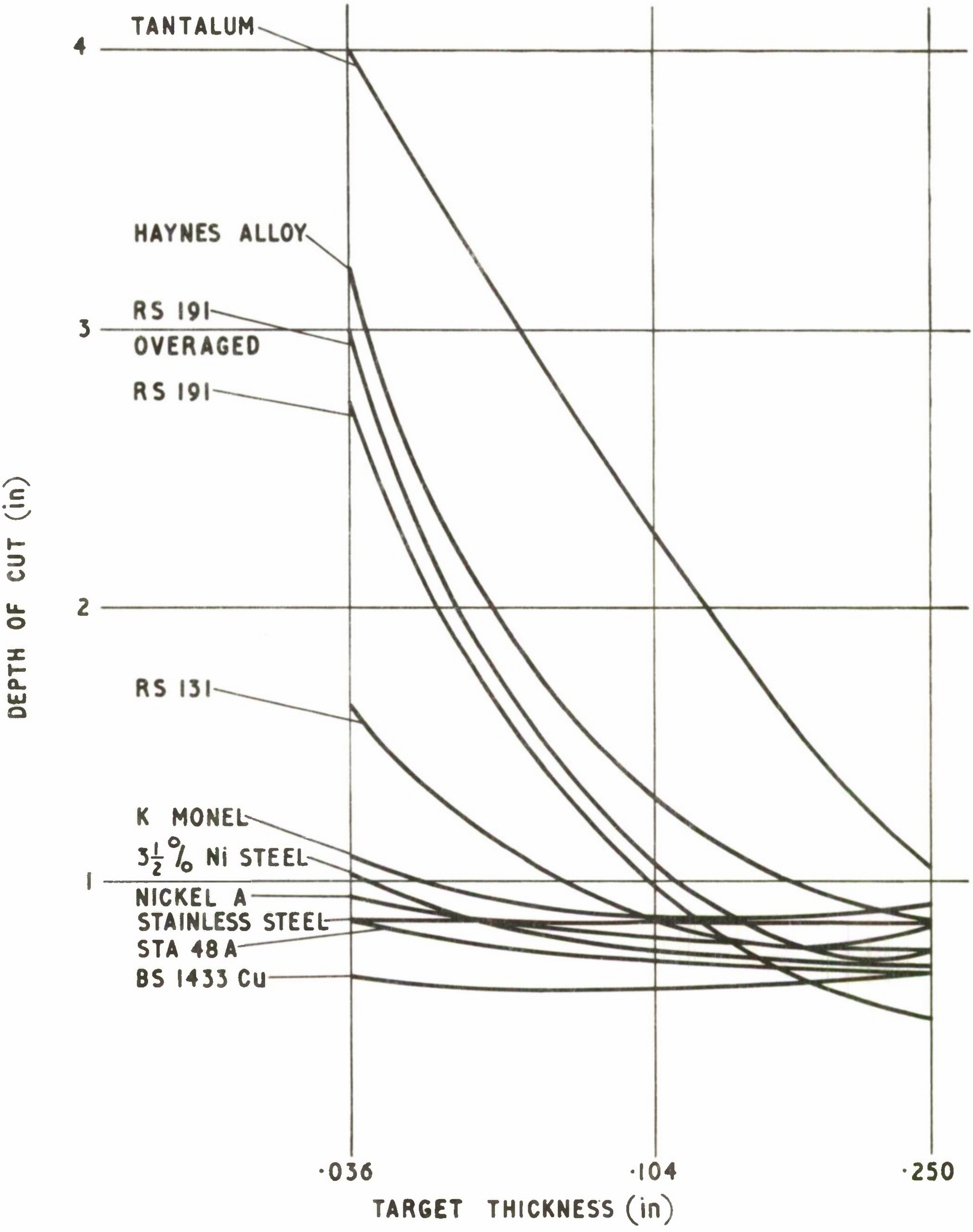

FIG. 8 DEPTHS OF CUT IN ALUMINIUM ALLOY TARGETS FROM HIGH VELOCITY RODS

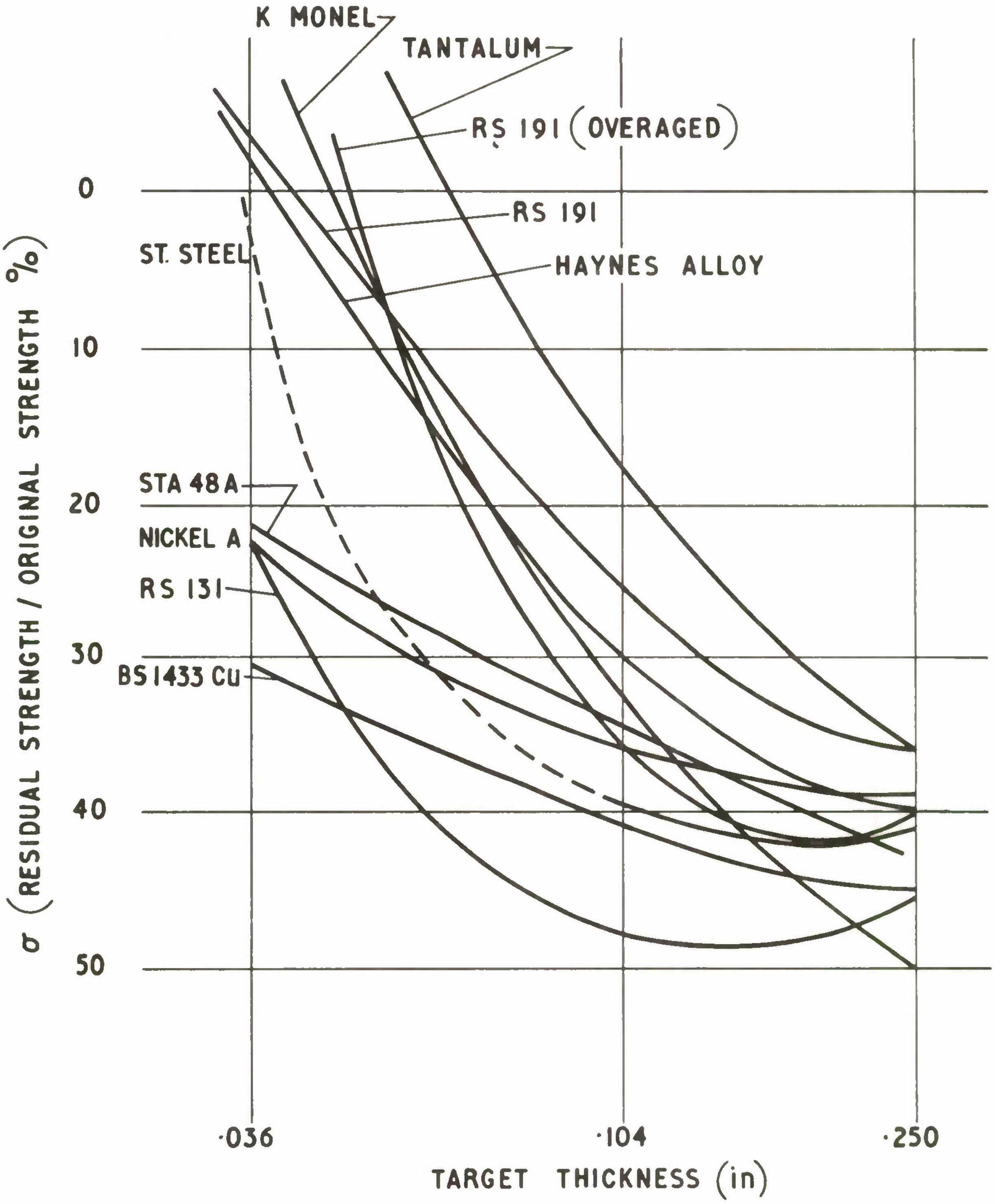

FIG. 9 RESIDUAL STRENGTHS OF ALUMINIUM ALLOY TARGETS FROM HIGH VELOCITY RODS

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FIG.10

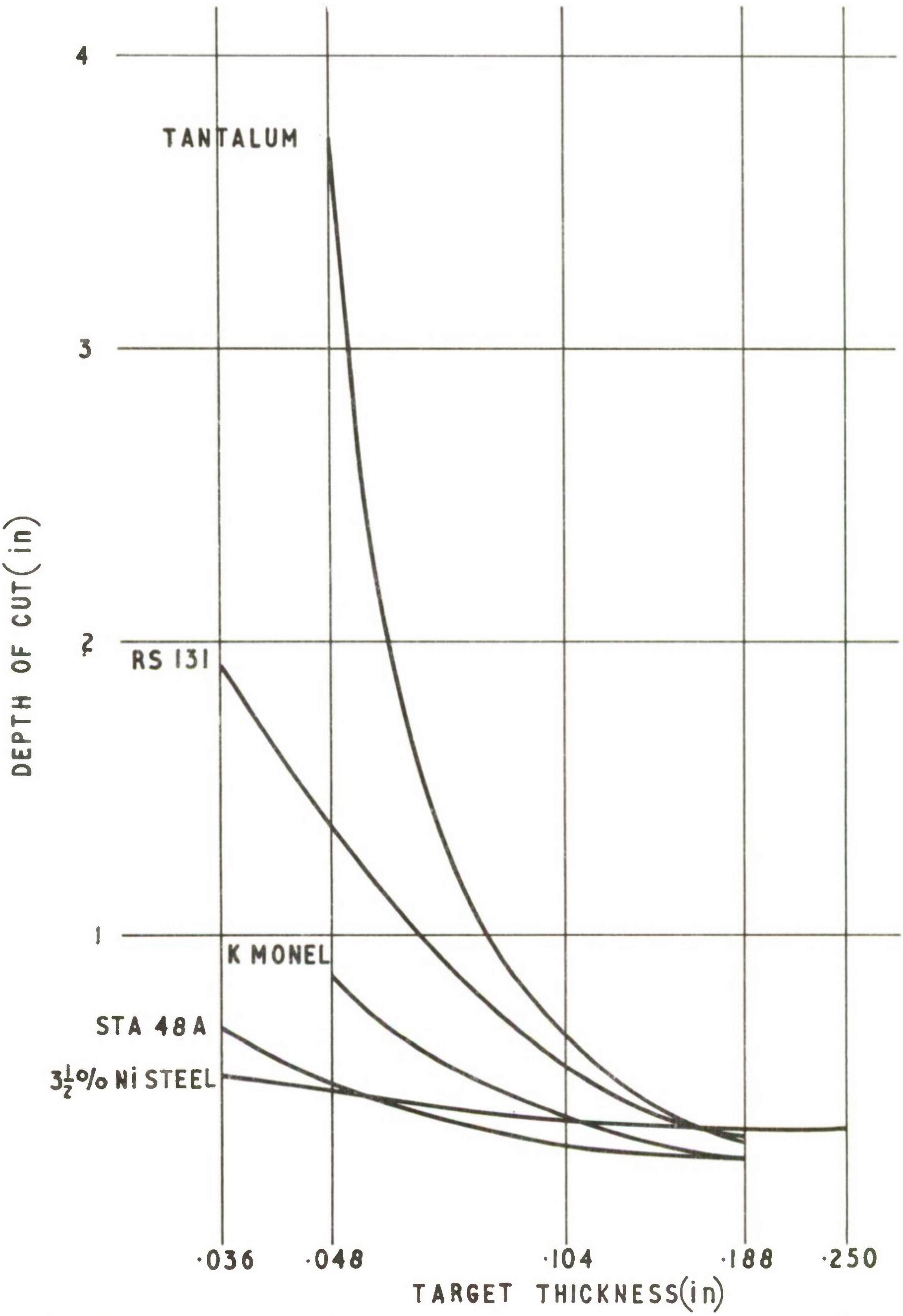

FIG.10 DEPTH OF CUT IN STAINLESS STEEL TARGETS FROM LOW VELOCITY RODS

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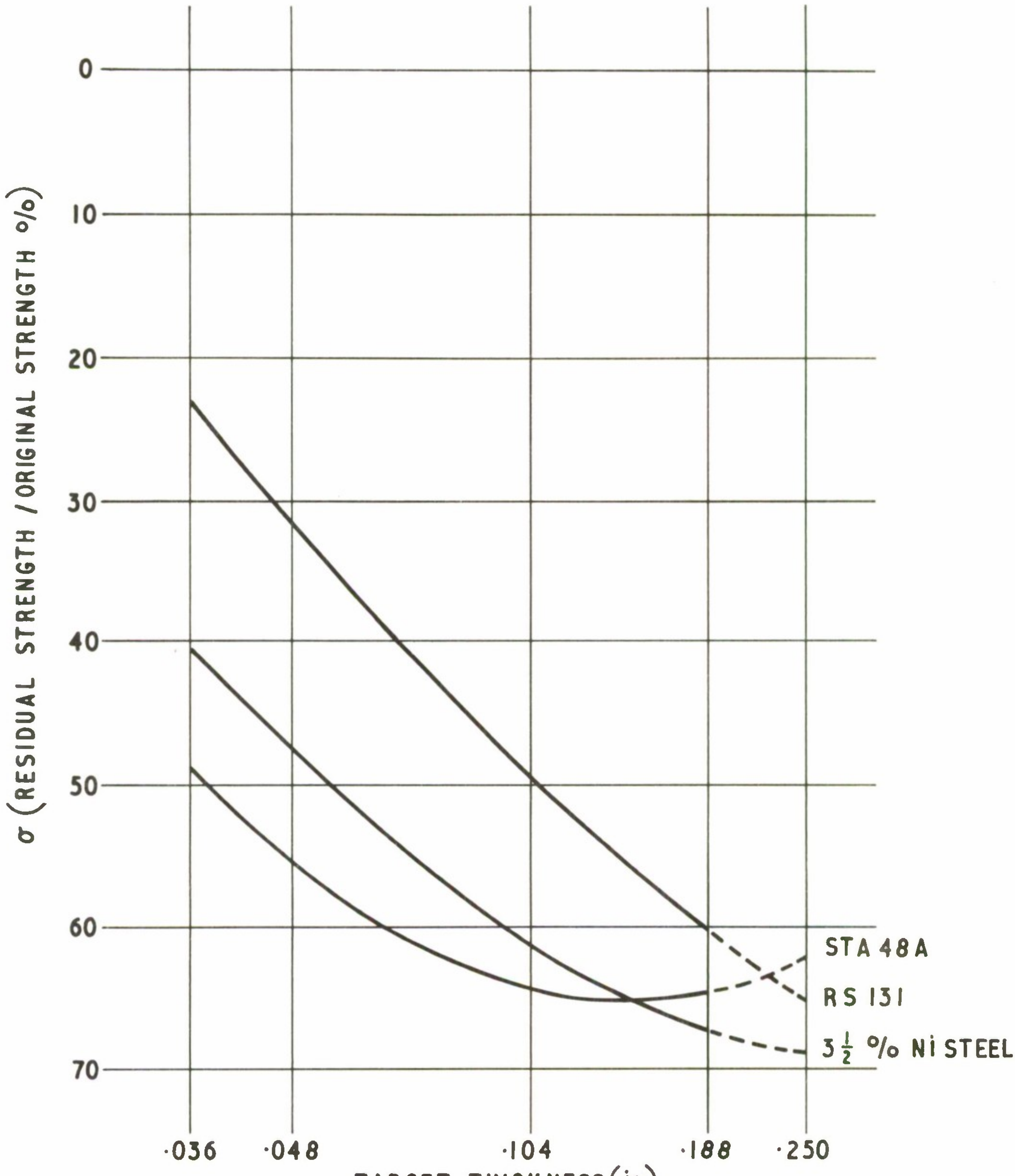

FIG. 11 RESIDUAL STRENGTHS OF STAINLESS STEEL TARGETS FROM LOW VELOCITY RODS

FIG.12

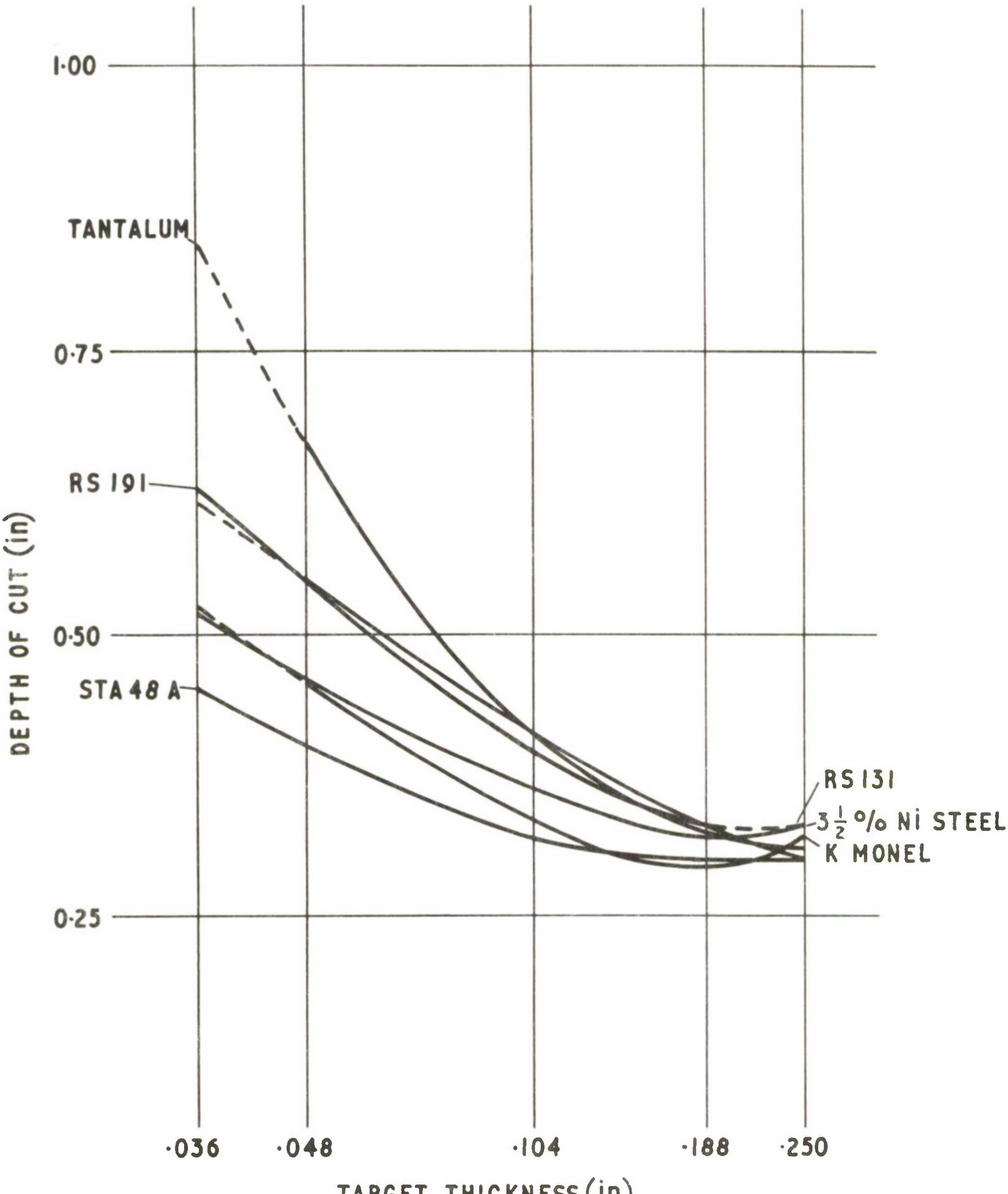

FIG. 12 DEPTH OF CUT IN STAINLESS TARGETS FROM MEDIUM VELOCITY RODS

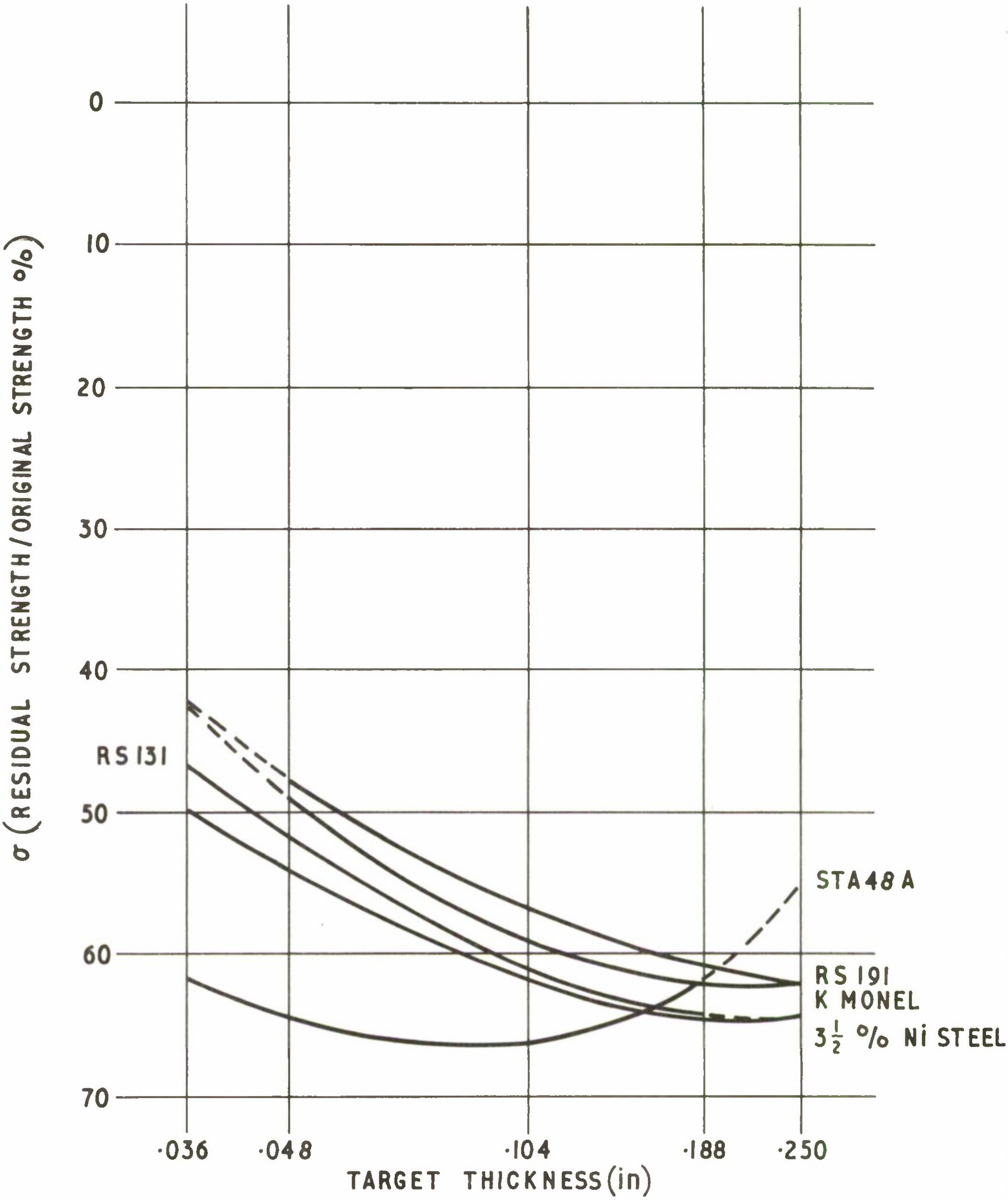

FIG.13 RESIDUAL STRENGTHS OF STAINLESS STEEL TARGETS FROM MEDIUM VELOCITY RODS

FIG. 14

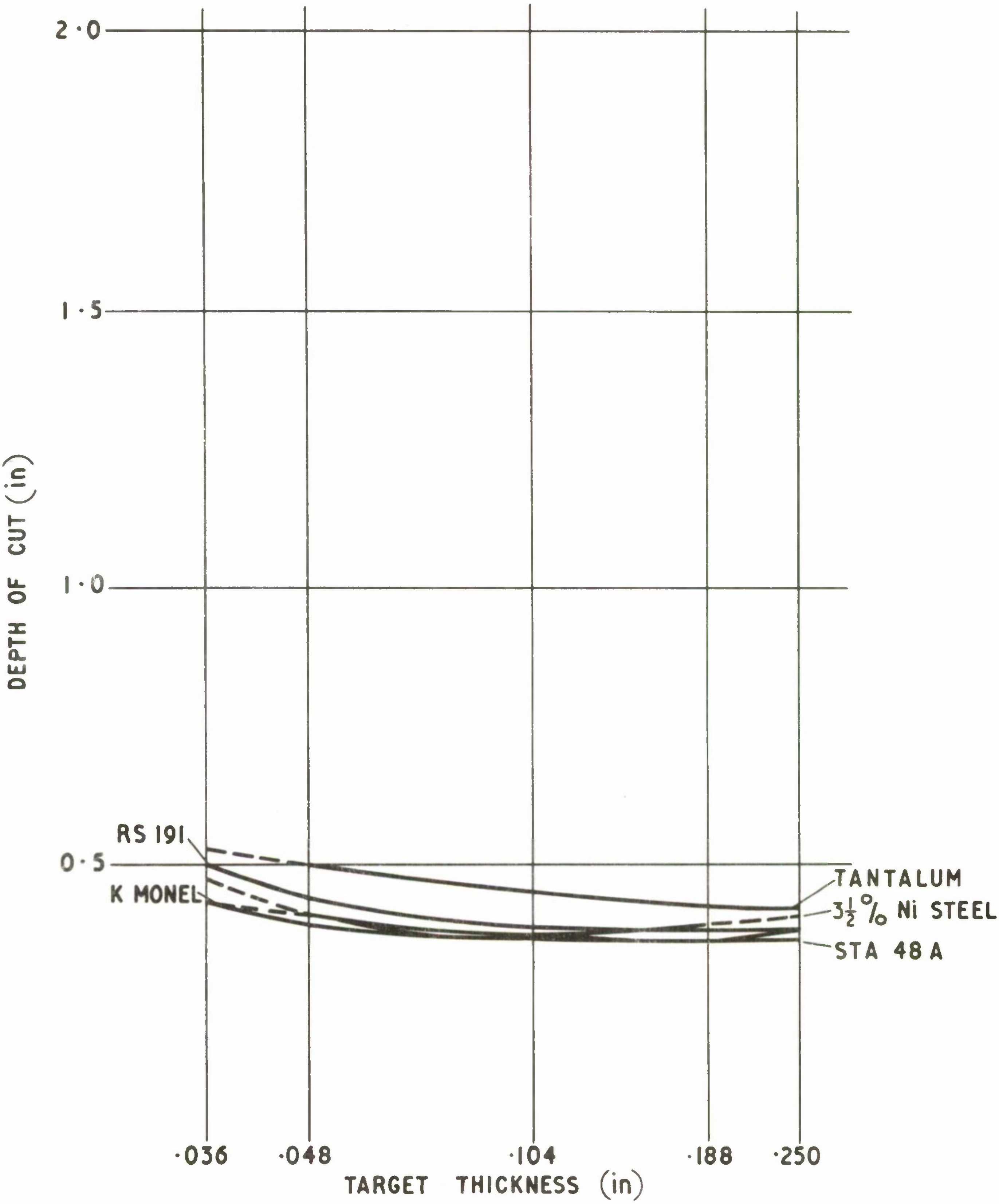

FIG. 14 DEPTHS OF CUT IN STAINLESS STEEL TARGETS FROM HIGH VELOCITY RODS

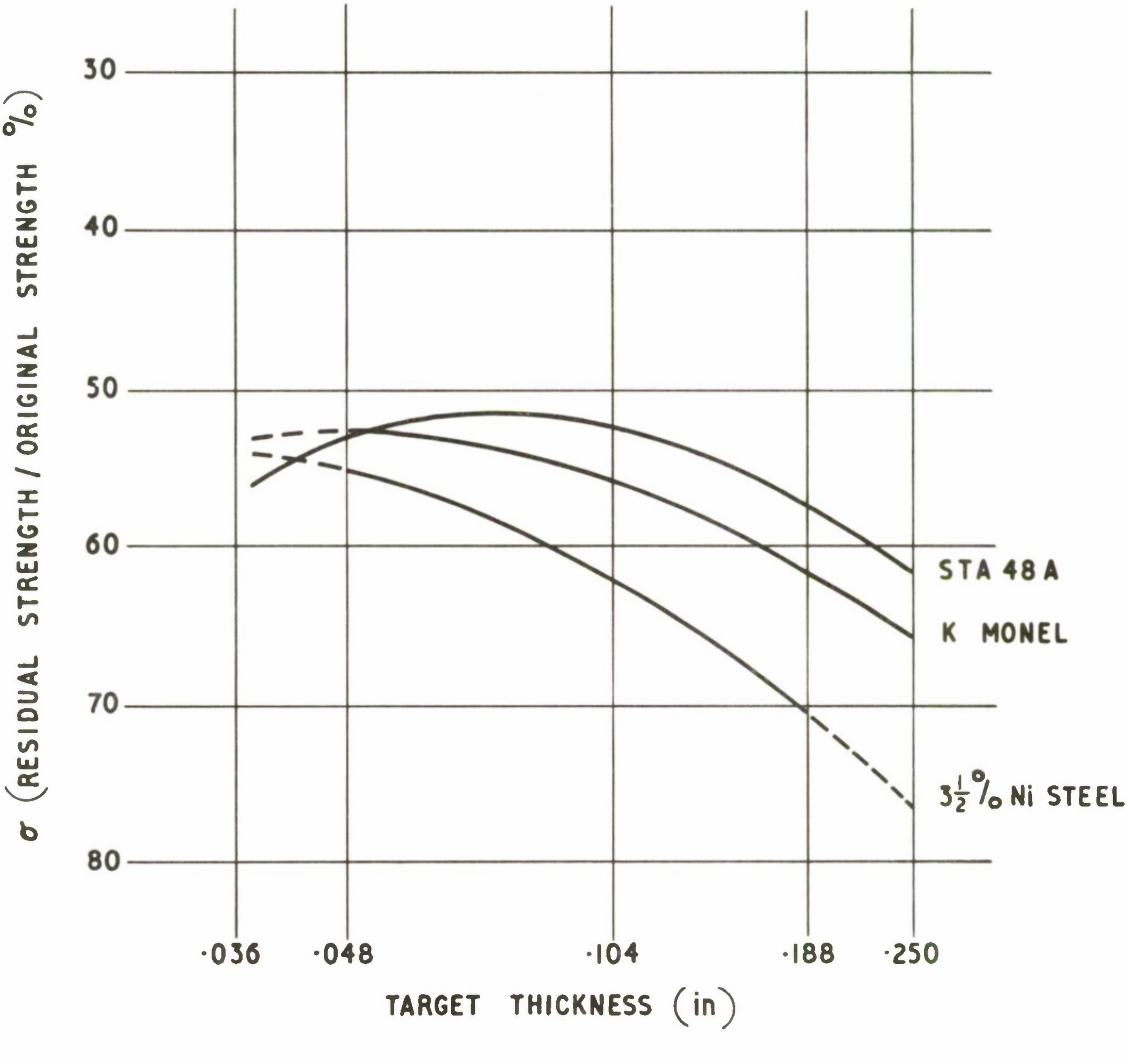

FIG. 15 RESIDUAL STRENGTHS OF STAINLESS STEEL TARGETS FROM HIGH VELOCITY RODS

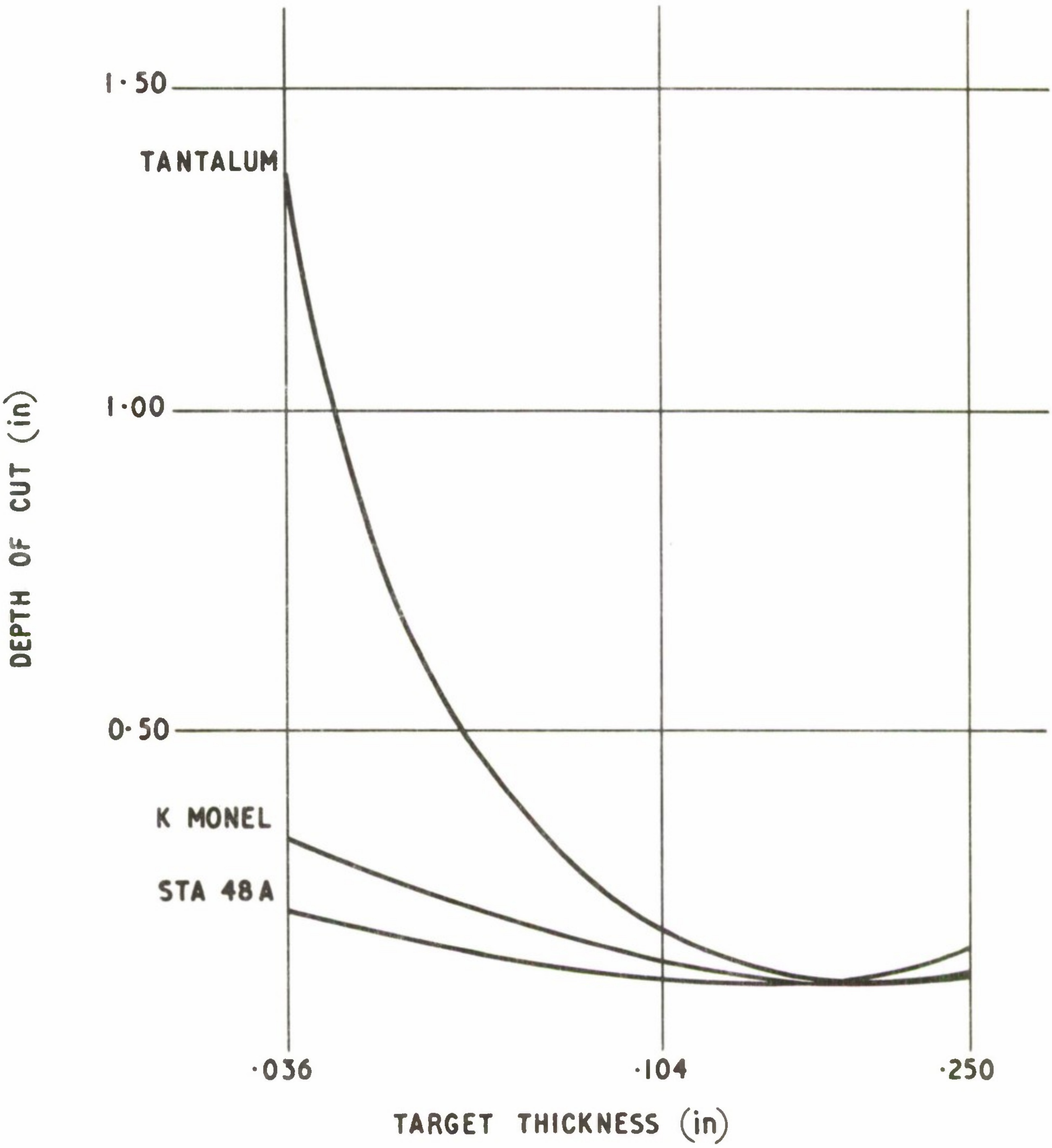

FIG. 16 DEPTHS OF CUT IN ROCKET STEEL TARGETS FROM LOW VELOCITY RODS

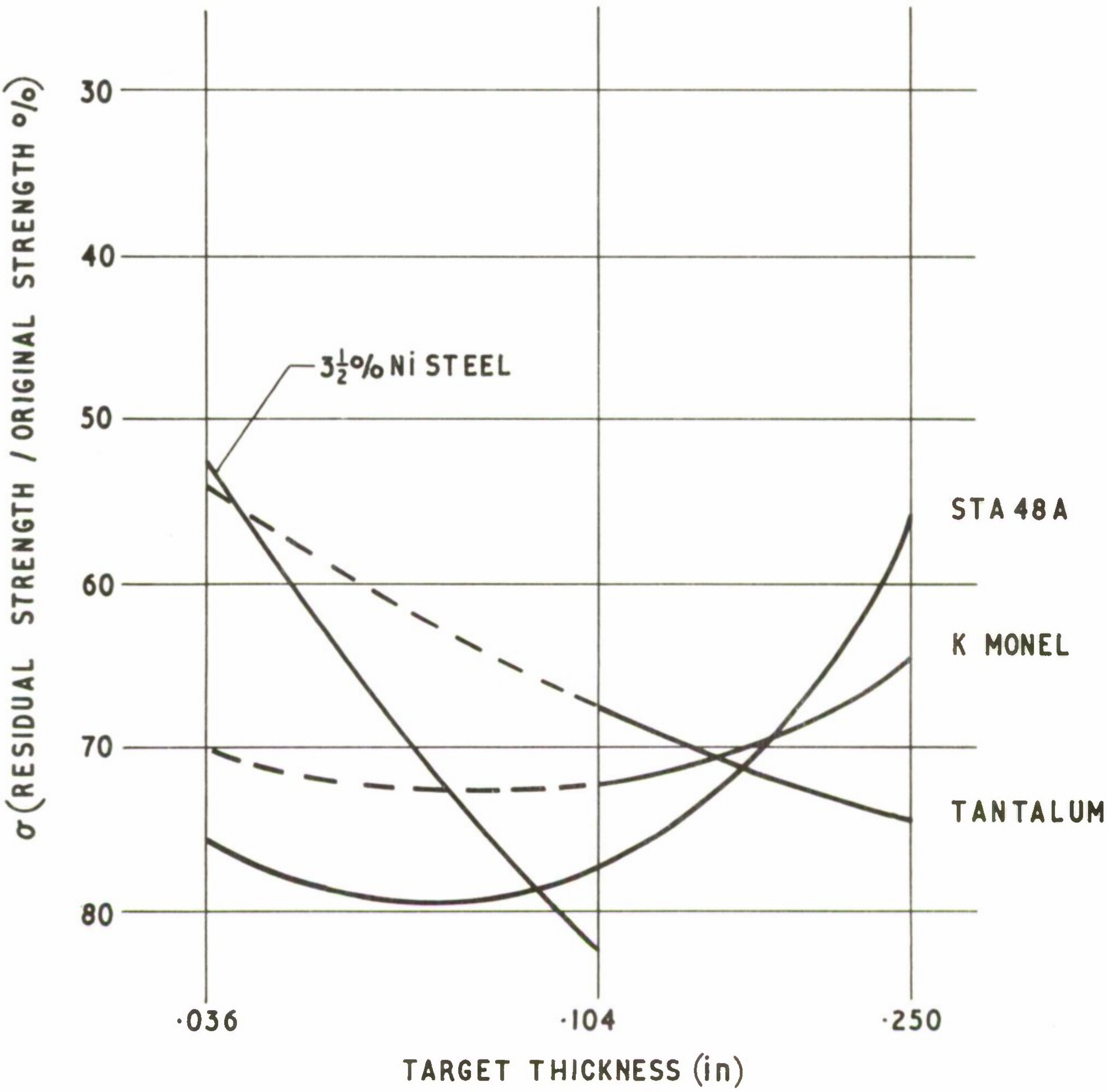

FIG.17 RESIDUAL STRENGTHS OF ROCKET STEEL TARGETS FROM LOW VELOCITY RODS

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FIG.18

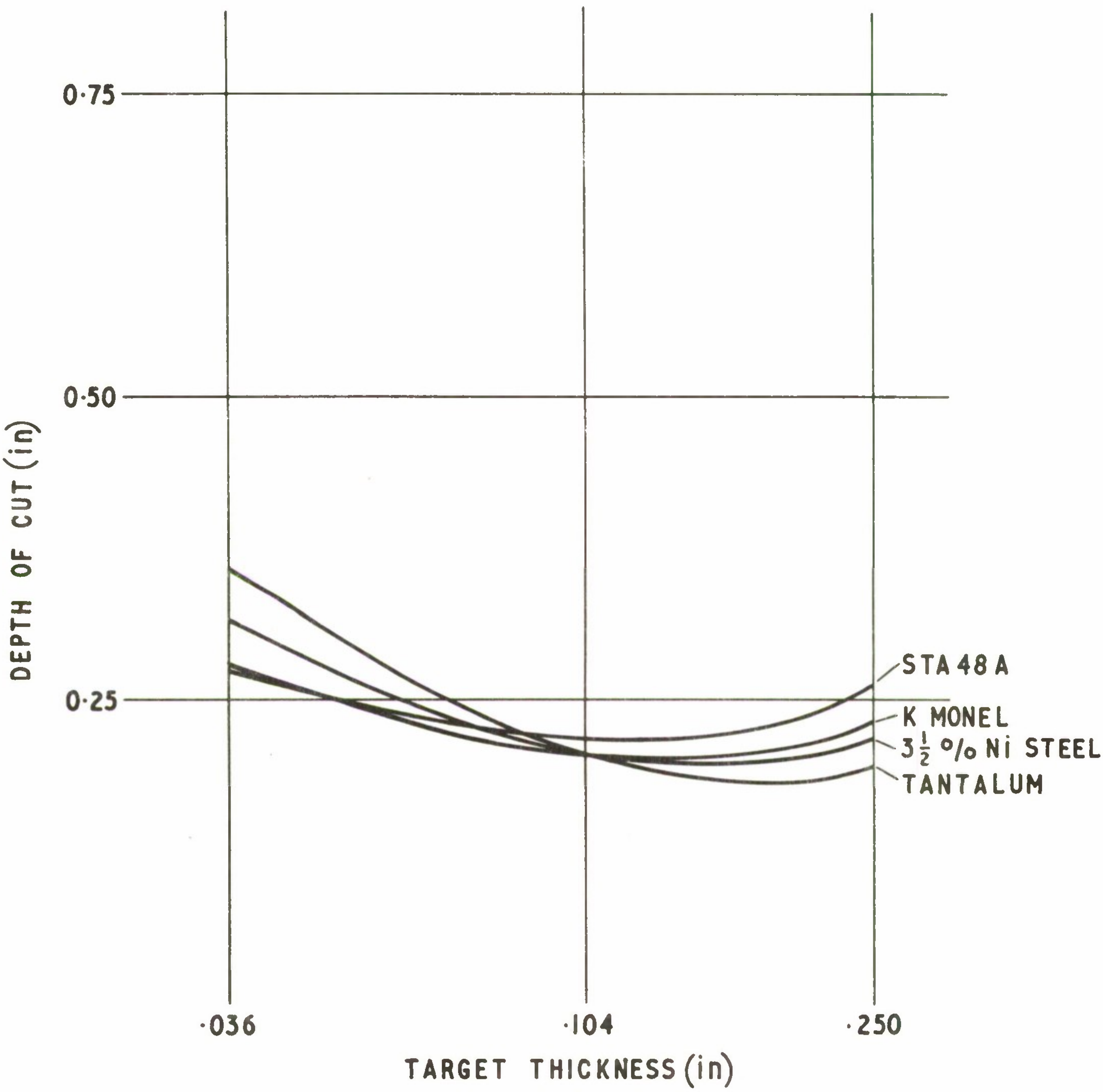

FIG. 18 DEPTHS OF CUT IN ROCKET STEEL TARGETS FROM MEDIUM VELOCITY RODS

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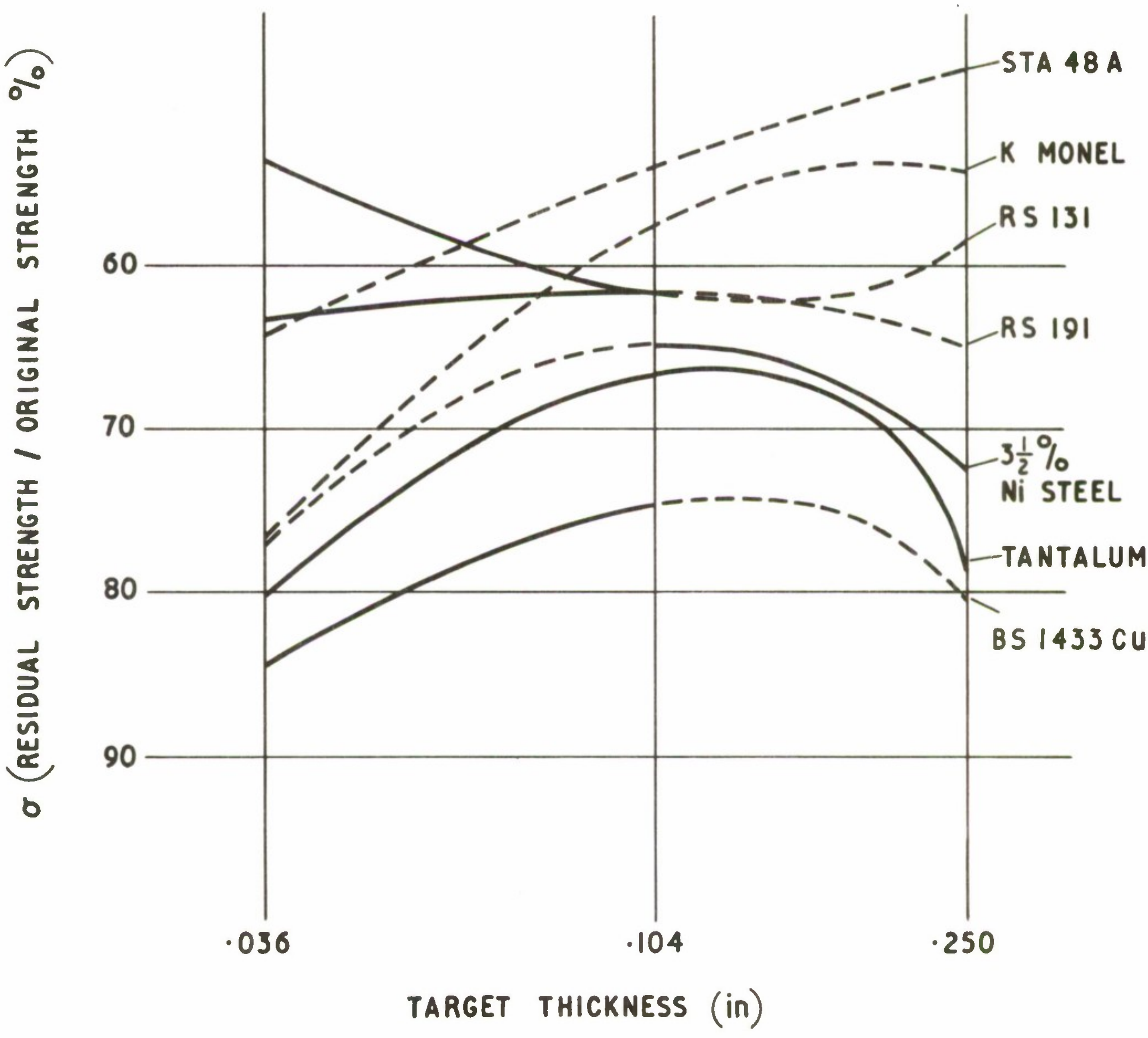

FIG. 19 RESIDUAL STRENGTHS OF ROCKET STEEL TARGETS FROM MEDIUM VELOCITY RODS

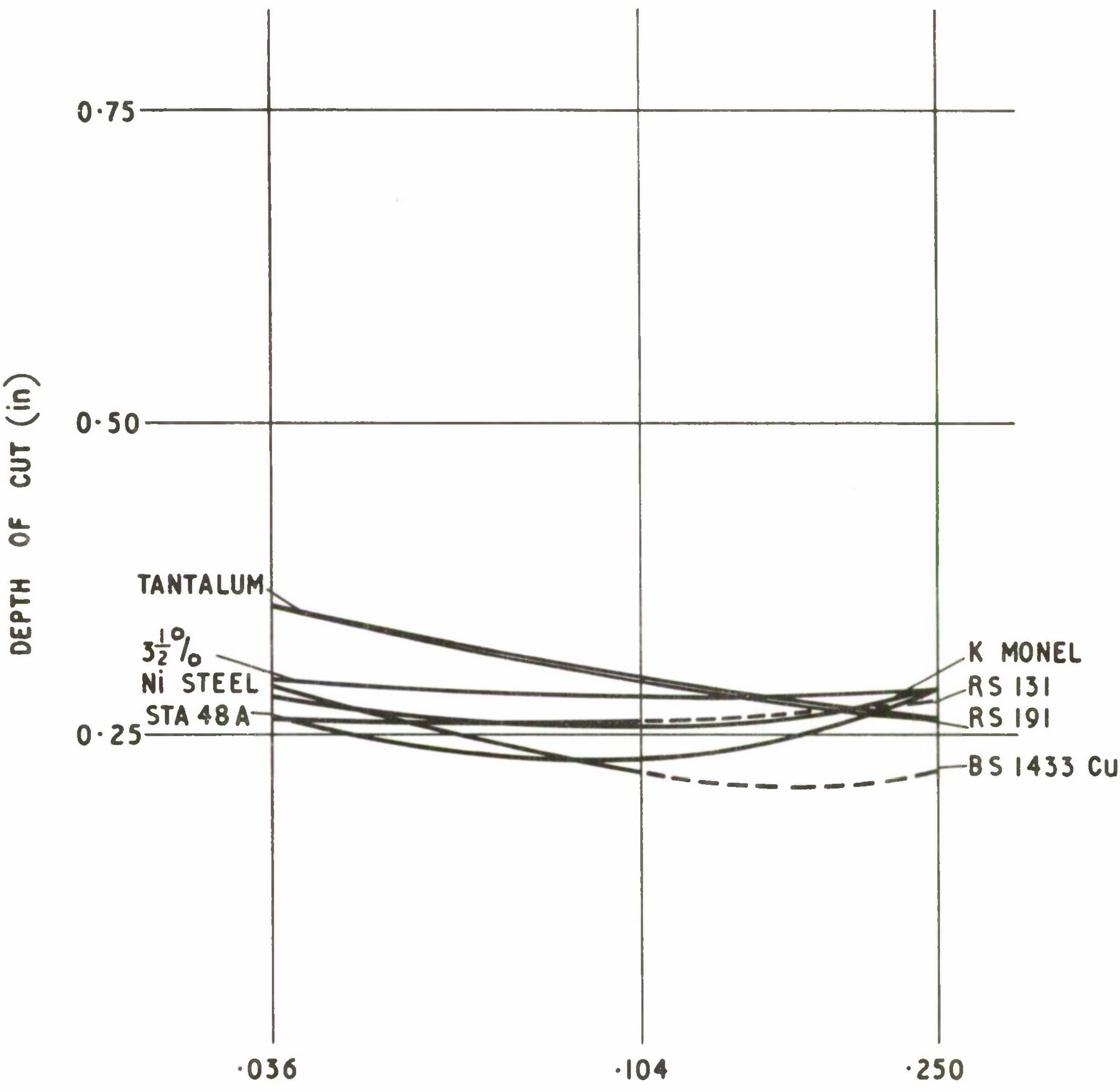

FIG. 20 DEPTHS OF CUT IN ROCKET STEEL TARGETS FROM HIGH VELOCITY RODS

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FIG. 21

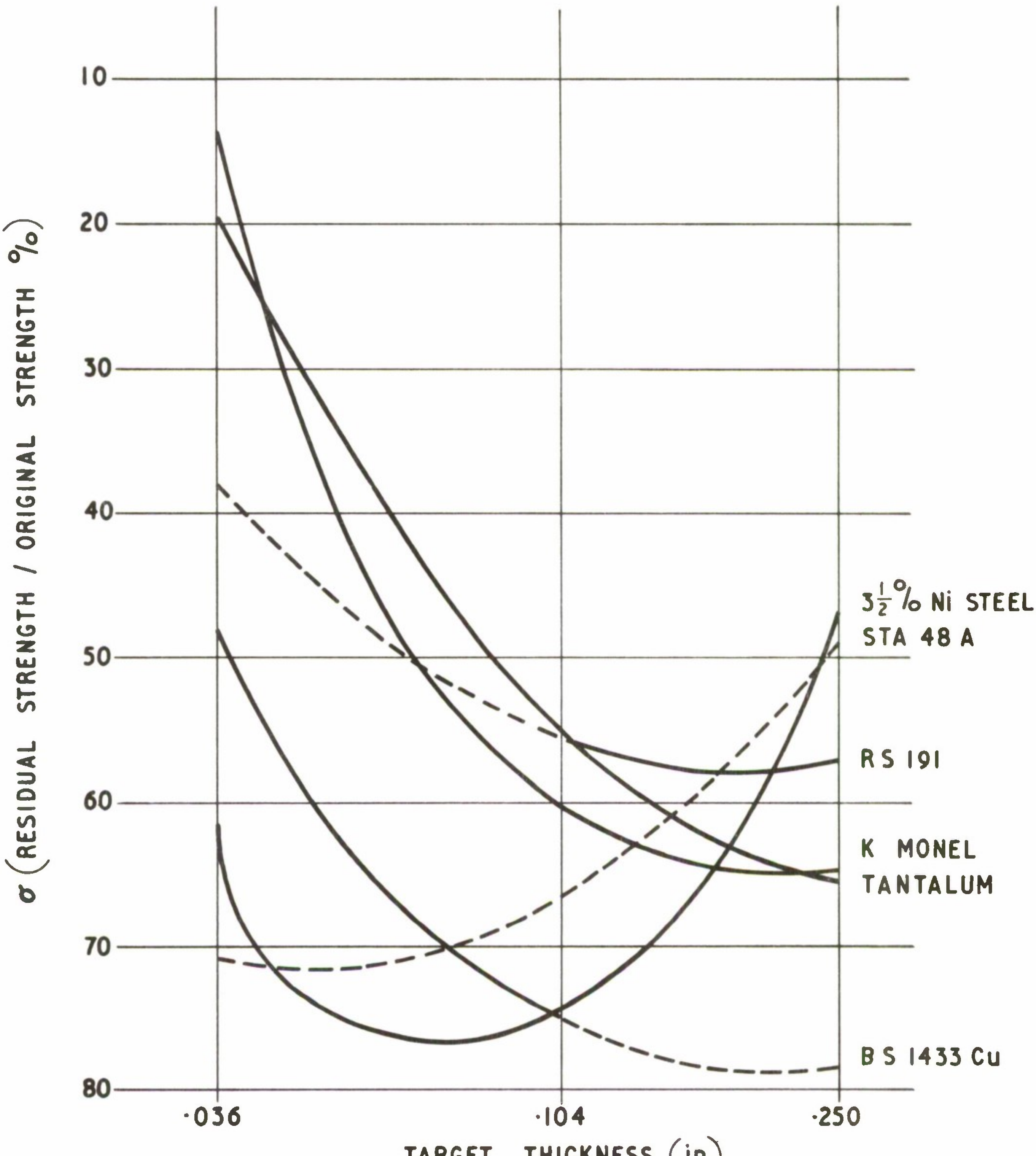

FIG. 21 RESIDUAL STRENGTHS OF ROCKET STEEL TARGETS FROM HIGH VELOCITY RODS

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FIG.22

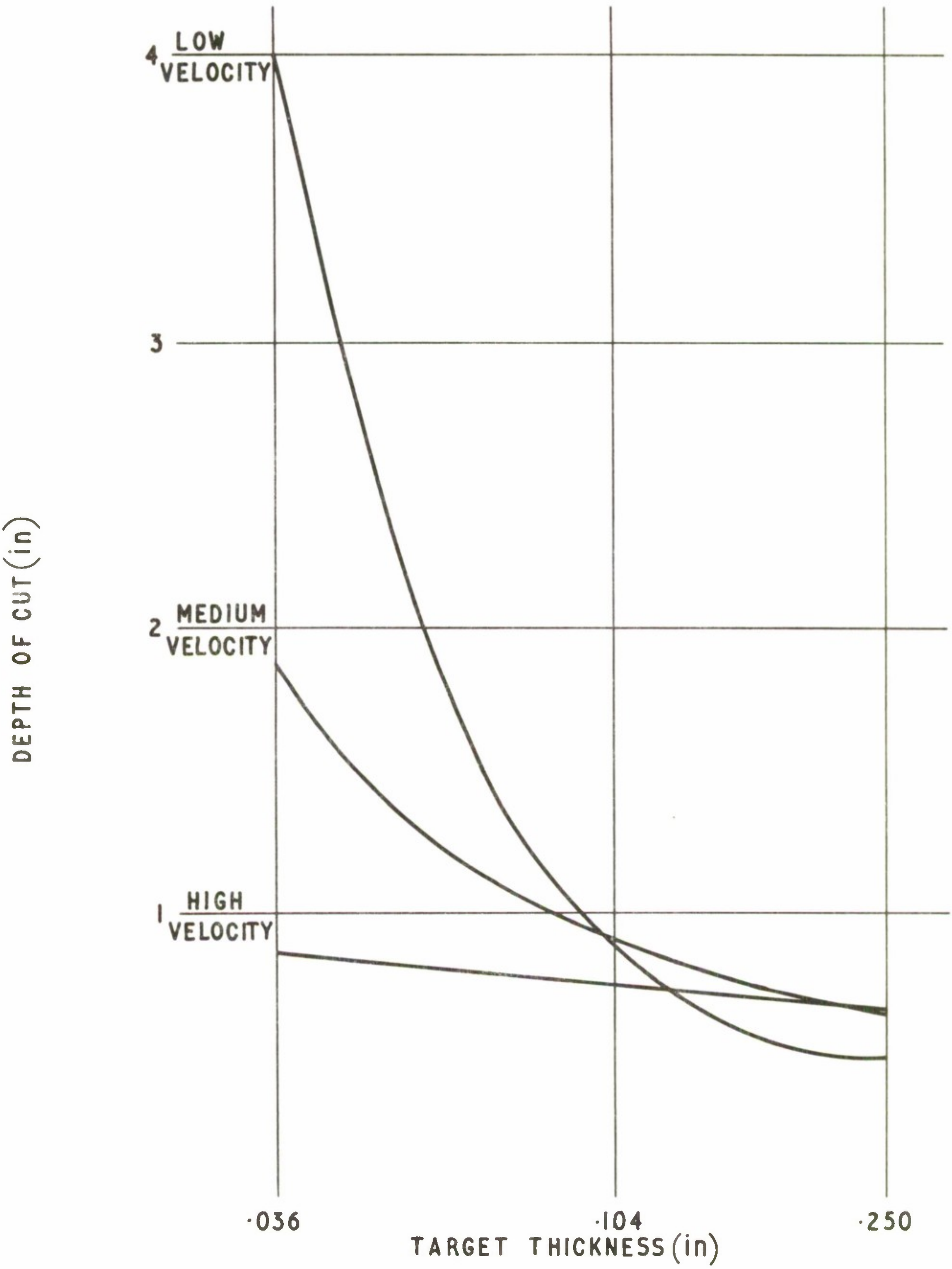

FIG.22 STA 48A RODS AGAINST ALUMINIUM ALLOY TARGETS–EFFECT OF VELOCITY ON DEPTH OF CUT

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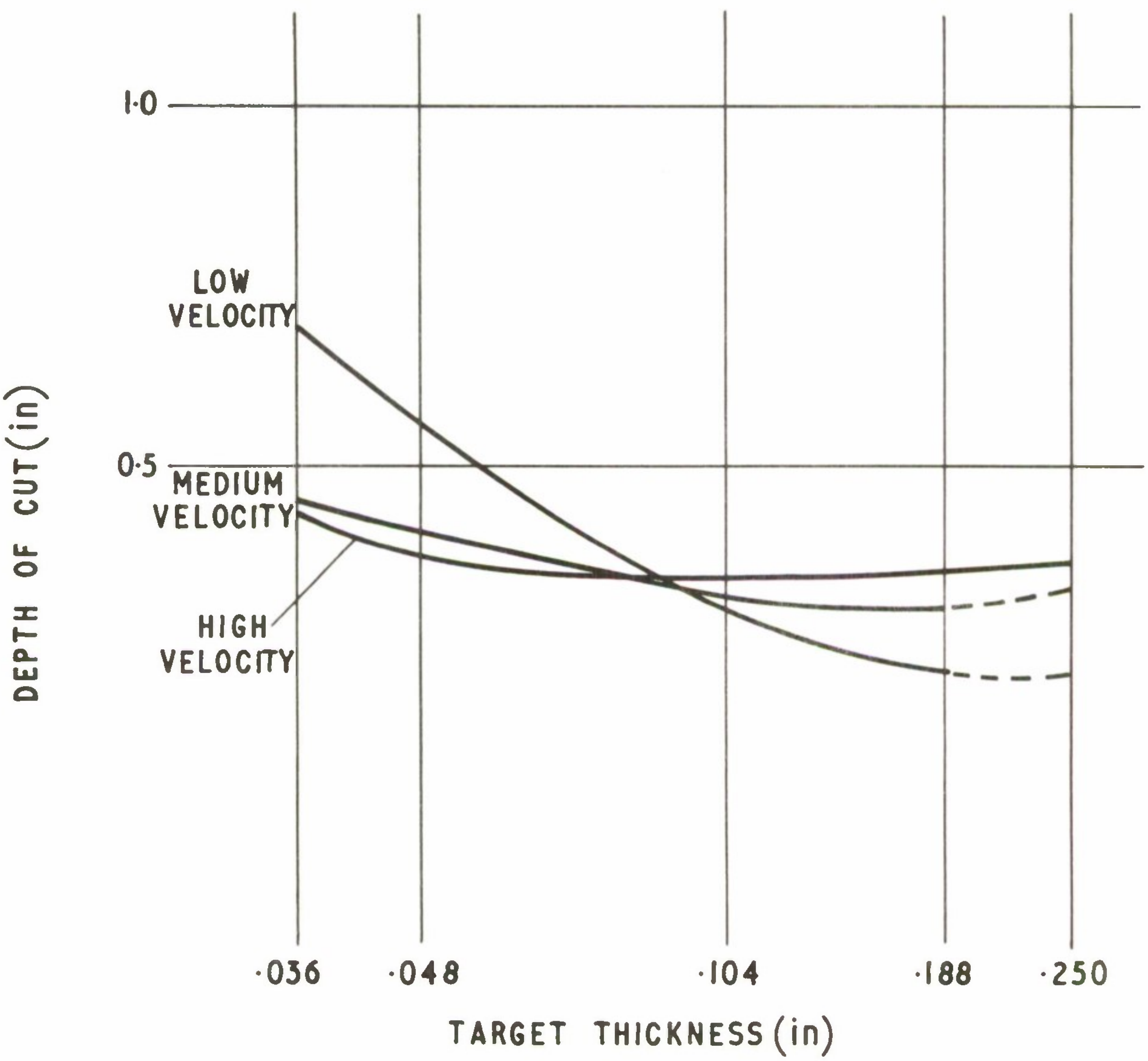


FIG.23 STA48A RODS AGAINST STAINLESS STEEL TARGETS – EFFECT OF VELOCITY ON DEPTH OF CUT

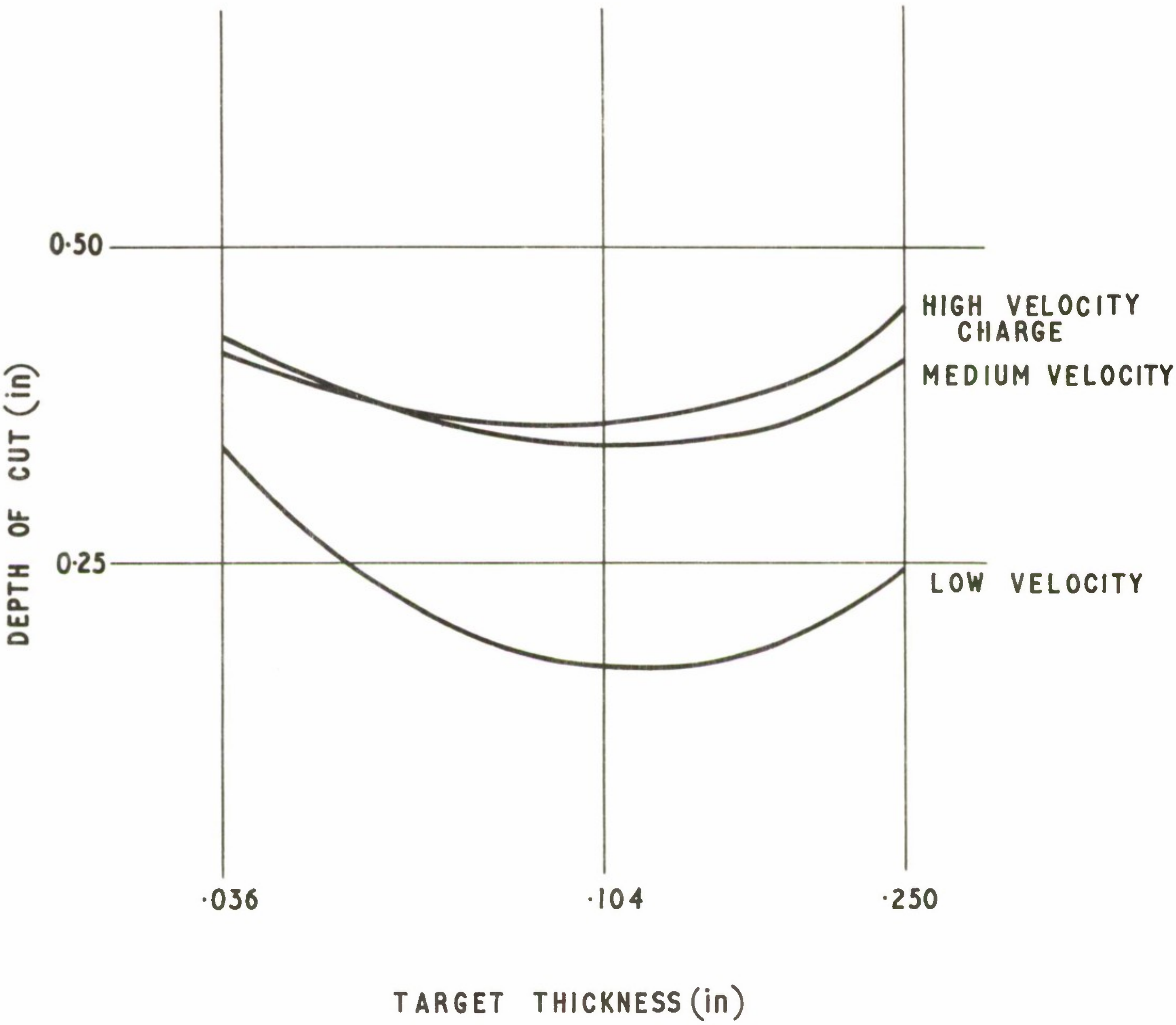


FIG. 24 STA 48A RODS AGAINST ROCKET STEEL- EFFECT OF VELOCITY ON DEPTH OF CUT

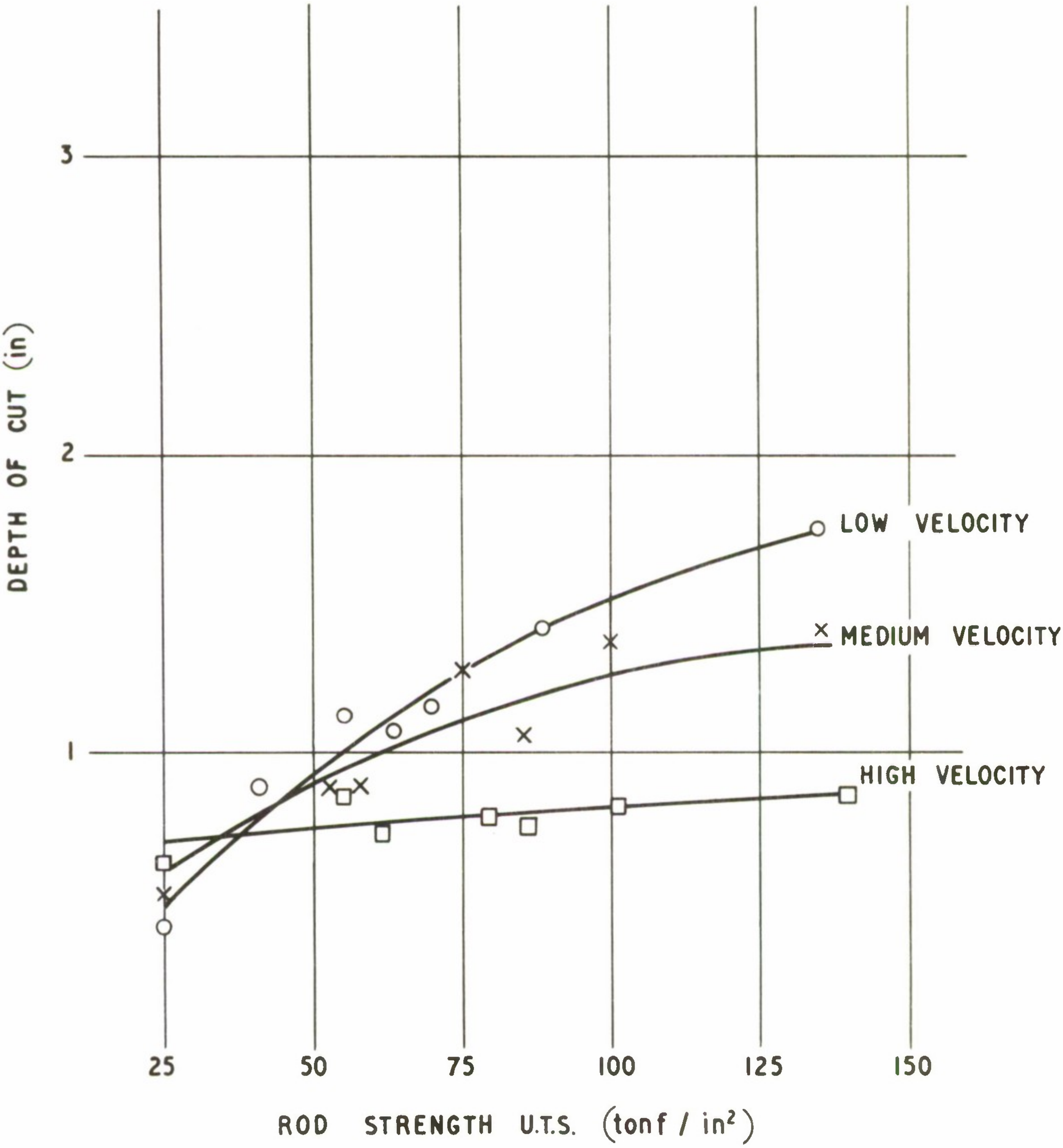


FIG. 25 0·104 in ALUMINIUM ALLOY TARGETS—EFFECT OF ROD STRENGTH ON DEPTH OF CUT

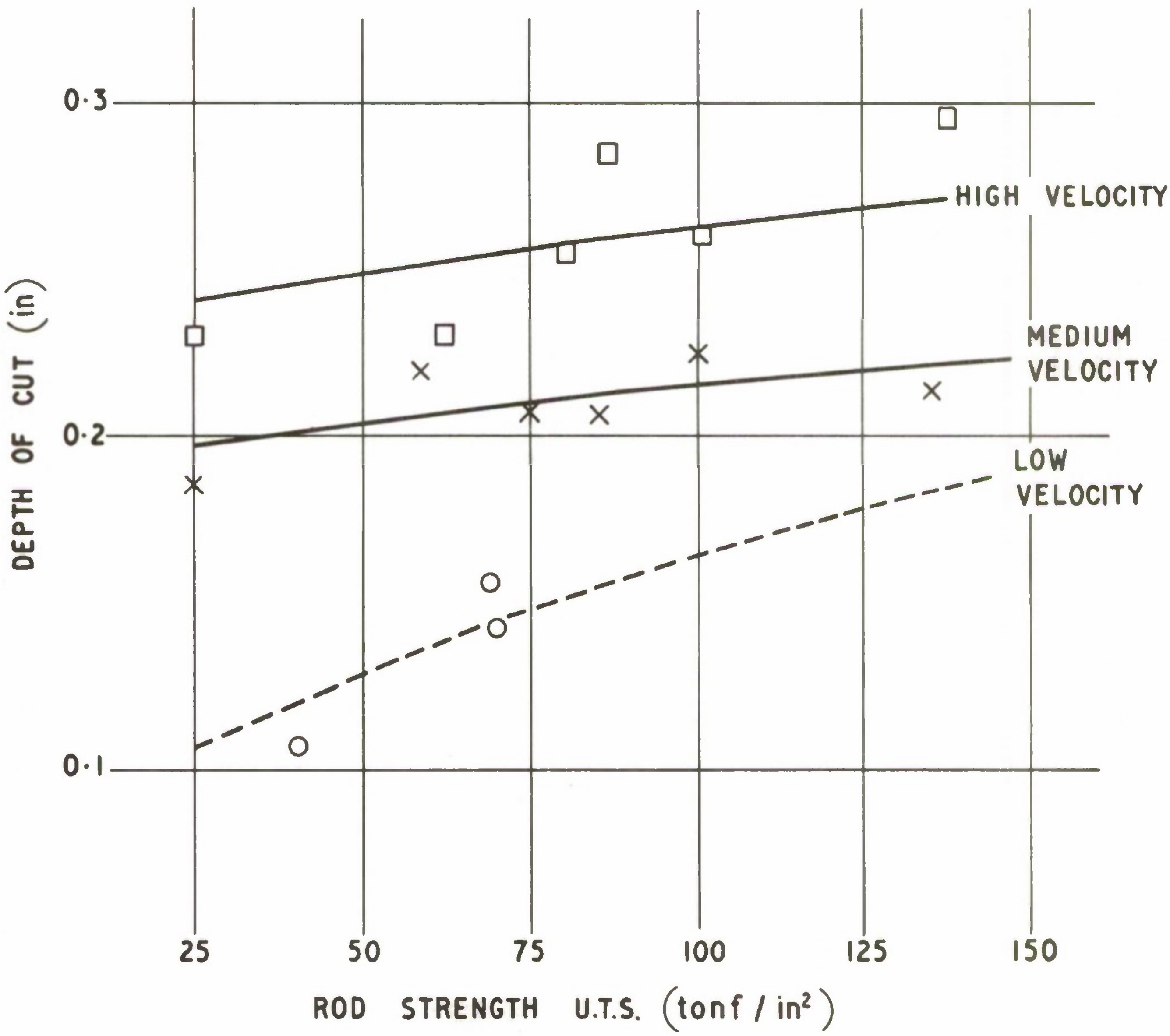
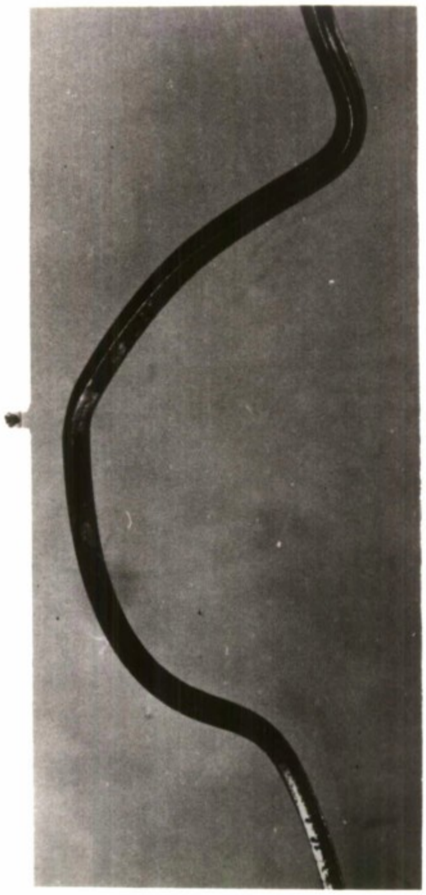
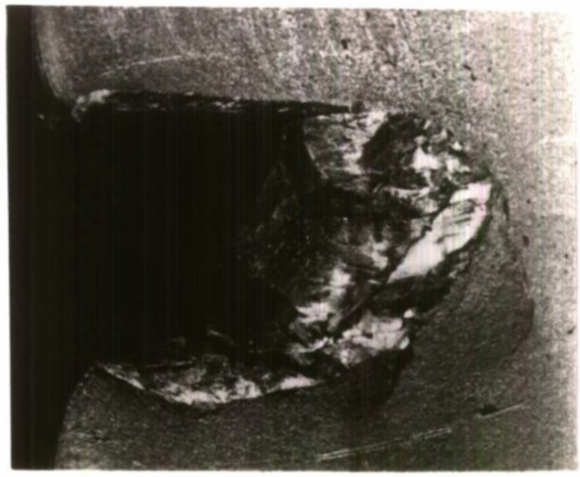


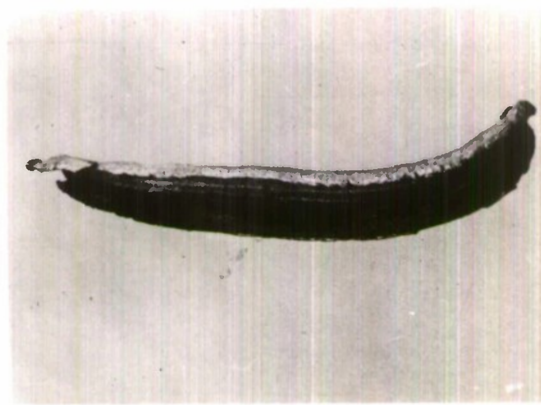
FIG. 26 0·104 in ROCKET STEEL TARGETS — EFFECT OF ROD STRENGTH ON DEPTH OF CUT



(a) ROD AFTER DEFEATING 4 in TARGET



(b) PIECE OF ROD TRAPPED IN TARGET



(c) PIECE OF ROD ASSOCIATED WITH THICK TARGET

(d) BROKEN ROD — PRINCIPALLY TENSILE FAILURE

(e) BROKEN ROD — PRINCIPALLY SHEAR FAILURE

FIGS. 27 (a-d) RODS AFTER ATTACKING TARGETS

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Damage effectiveness of different rod materials against various targets, at a range of velocities.

S E Corbett

October 1970

Ten materials have been placed in an 'order of merit' for damage effectiveness should they be used for the rods on Continuous Rod Warheads, by projecting rods of the various materials from explosive charges at three strike velocities against three different target materials in three thicknesses.

The dependence of damage on rod strength, density and velocity is shown to vary with target strength and thickness.

The mechanism of damage is also discussed.

18 pp. 27 figs. 7 tabs. 5 refs.

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